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A STUDY OF HEAT TRANSFER FROM OIL GLOBULES TO A WATER BATH

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TO A WATER BATH

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NOMENCLATURE

A	Area, cm.^{2}
C_p	Specific heat, grm. cal./grm. $^\circ C$
d	Drop diameter, cm.
d_c	Critical diameter, see equation 13, cm.
e	Base of natural logarithms
h	Transfer coefficient, cal./sec.cm^2 $^\circ C$
g_c	Accleration due to gravity 980grms.mass.cm./sec.^{2}
k	Thermal conductivity, grm. cal./sec/cm. $^\circ C$
M	Mass, grms.
μ	Viscosity, dyne sec./cm^2
ρ	Density grms./cm.^{2}
$\Delta\rho$	$\rho_c - \rho_d$, grms./cm.^{3}
σ	Interfacial tension, degrees./cm.
Q	Heat, grm. cal/sec.
r_1	Radius of drop, cm.
Re	Reynolds number = $\frac{d.v.\rho}{\mu}$, dimensionless
Pr	Prandlt number = $C_p \cdot \mu / k$, dimensionless
Nu	Nusselt number = dh/k, dimensionless
We	Weber number = $v^2 \cdot d \cdot \rho \cdot / \sigma g_c$, dimensionless
Pe	Peclet number = $d.v. / \alpha$, dimensionless
Pe^1	Modified Peclet number = Pe $(1 + \mu d / \mu c)$ dimensionless
R	Thermal resistance, sec.cm.^{2} $^\circ C$/cal.

(continued)

NOMENCLATURE

α Thermal diffusivity = $k/\rho C_p$, $cm^2/sec.$

t Temperature, ^{o}C

v Velocity of drop, for V_1 see equation 11, for V_{11} see equation 12, cm./sec.

Subscripts

d Dispersed phase

c Continuous phase

o Observed value

e Experimental value

1 Value for radial conduction mechanism.

2 Value for radial conduction with outside film.

3 Value for internal circulation mechanism.

4 Value for internal circulation with outside film.

F Natural convection

SUMMARY

Chemical processes generally require heat and/or mass transfer in some phase of their operation. Estimation of the transfer rate requires knowledge of the transfer mechanism, and the transfer coefficient.

This experiment was a study of heat transfer from a dispersed phase to a continuous phase. A white mineral oil was heated and introduced into an insulated water bath. An experimental transfer resistance was determined, and compared with four theoretical resistances. It was found that two transfer mechanisms existed: (1) the liquid drops behaved similarly to solid spheres, and the transfer mechanism was therefore that of radial conduction with a continuous phase film resistance; and (2) the liquid drops possessed an internal circulation pattern, and a continuous phase film resistance. The radial conduction mechanism existed for a Reynolds number range of 280 through 530. For Reynolds numbers of 530 and greater, the internal circulation mechanism was present. The shift in mechanism appears to have been caused by the increased drag on the liquid drops. At the Reynolds number of 530, the skin friction seems to have become dominant in the surface forces thus providing the energy required to develop, and maintain internal circulation within the drop.

The experiments suggest that if the ratio of the viscosities of the dispersed and the continuous phases is large, the controlling resistance will lie in the dispersed phase. For a transfer process, involving a liquid drop rising through a continuous liquid phase, it would seem desirable to obtain as large a value of drag as is practical. This would

tend to induce internal circulation which in turn greatly improves the heat transfer coefficient.

CHAPTER I

INTRODUCTION

Chemical processes generally require heat and/or mass transfer in some step of their operations. Many of these processes involve transfer between a continuous phase and a dispersed phase such as a liquid drop, a gas bubble, or a solid sphere. This study was carried out to evaluate the heat transfer between oil globules and a water bath.

The transfer rate of an exchange process between continuous and dispersed phases is difficult to determine and decidedly unpredictable. The rate is dependent on the area of contact, the effective driving force, and the transfer coefficient. Determination of the average contact area requires data on the frequency distribution of sizes of the dispersed phase, the rate of rise or fall of the dispersed fluid, and the circulation rate of the continuous phase. The effective driving force will vary with the type of transfer; for example, in heat transfer the temperature gradient is the driving force, while in mass transfer the concentration gradient is assumed to be the driving force. Measurement of the driving force for mass transfer is complicated by two factors: the accumulation of trace contaminants at the interface of the phases, and the difficulty in determining the flow patterns of the continuous phase. The transfer coefficient, in the form of a Nusselt number, may be known from previous work or may be determined by experiment.

This study was concerned with heat transfer from a flowing dispersed phase to a stagnant continuous phase. The experimental conditions allowed evaluation, and limited control, of the average contact area and the driving force. Therefore, this work was a study of the transfer coefficient.

Review of the literature.--Heat transfer to or from a liquid drop is affected by several factors: (1) the extent of internal circulation in the drop, (2) the resistance of the film surrounding the moving drop, and (3) the effective thermal diffusivity within the drop. The transfer coefficient is directly influenced by the same factors. A knowledge of the transfer mechanism is necessary for the evaluation of the transfer coefficient. In 1911 Hadamard (1) investigated the hydrodynamics of falling drops undergoing viscous circulation and proposed a pattern for this internal motion. Several investigators have developed proofs of this circulation, e.g. Spells (2) has presented photographs of the circulation pattern, Garner and Skelland (3) have developed an approximation for predicting the existance of circulation, and Kronig and Brink (4) have developed a mathematical model for Hadamard's pattern.

Garner's and Skelland's (3) approximation is a convenient plot of transitional Reynolds number versus droplet viscosity. The authors are of the opinion that this transitional Reynolds number is dependent on the viscosity of the continuous phase, the viscosity of the dispersed phase, and either the interfacial tension between the two fluids or the character of the interface. The approximation shows an increasing Reynolds number for increasing drop viscosity.

Hughes and Gilliland (5) made a review and analysis of the mechanics of drops. The review suggests that if the fluid within the drop is very viscous, the amount of energy which has to be transferred in order to induce circulation is large and circulation effects are therefore small. However, the action of the skin friction is to provide the energy to overcome this viscous damping. This circulation becomes appreciable whenever the skin friction is a major portion of the surface forces.

Handlos and Baron (6) studied theoretically and experimentally mass and heat transfer from drops in liquid - liquid extration. They developed two transfer coefficients, one expressing the effect of internal circulation within the drop and the other evaluating the resistance of the film surrounding the drop.

Calderbank and Korchinski (7) evaluated the continuous phase resistance, and the effective thermal diffusivity obtained during the fall of circulating liquid drops. They found the continuous phase resistance to be essentially the same as the resistance for mercury drops under the same conditions, and the effective thermal diffusivity to be a multiple, 2.25, of the molecular diffusivity. Their work also indicated that drop oscillation would increase the drag coefficient, the continuous phase heat transfer coefficient, and the effective diffusivity within the drop.

McDowell and Myers (8) studied the process of heat transfer to liquid drops rising through another liquid, and drew the following conclusions:

1. If the viscosity of the liquid in the drop is low enough compared with the viscosity of the continuous-phase fluid, the liquid in the drop will circulate.

2. Circulation lowers the resistance to heat transfer.

3. If the thermal conductivity of the continuous-phase liquid

surrounding the drop is low compared with that of the liquid within the drop, an appreciable part of the resistance to heat transfer will be in the film outside the drop.

Evaluation of the experimental data.--The most direct method of evaluating the experimental data is a comparison of the observed transfer coefficients and the transfer coefficients calculated for the possible transfer mechanisms. The literature (8) offers four transfer mechanisms:

(1) internal radial conduction with no appreciable outside film resistance,

(2) internal radial conduction plus outside film resistance,

(3) internal circulation with no appreciable outside film resistance, and

(4) internal circulation with outside film resistance.

The calculation of the radial conduction contribution to the transfer mechanism was performed with the assumption that the liquid drop was essentially a solid sphere. Schneider (9) has presented the following equation as the instantaneous surface heat rate for a solid sphere under the condition of negligible surface resistance:

$$\frac{Q_1 \quad r_1}{k\ A_1\ (t_1 - t_i)} = 2 \sum_{n=1}^{\infty} e^{-(n\,\pi)^2\,\theta} \tag{1}$$

The transfer coefficient may be represented by

$$h_d = (2 \sum_{n=1}^{\infty} e^{(n\pi)^2 \theta}) (k_1/r_1) \tag{2}$$

Kramers (10) developed an empirical equation for the film coefficient of a fluid flowing past steel spheres. His correlation is as follows:

$$Nu = 2.0 + 1.3 (Pr)^{0.15} + 0.66 (Pr)^{0.31} (Re)^{0.50} \tag{3}$$

This is probably as good an approximation as possible of the film coefficient for heat transfer between a continuous phase and a stagnant drop.

Handlos and Baron (6) have developed transfer coefficients for a liquid drop whose interior has a circulation pattern. The coefficient for the resistance of the outside film is

$$Nu_o = 1.13 \sqrt{Pe_o} \tag{4}$$

The effect of internal circulation is expressed by

$$Nu_d = 0.00375 \; Pe^1{}_d \tag{5}$$

Unfortunately equation 5 failed to produce manageable results in the evaluation of the experimental data. Therefore, the molecular diffusivity in equation 2 was multiplied by 2.25. The resulting expression was used to represent the transfer coefficient for internal circulation.

For the comparison, the transfer coefficients are expressed as overall transfer resistances by the use of the usual relationship:

$$\frac{1}{U} = \frac{1}{h_c} + \frac{1}{h_d} = R \tag{6}$$

Accordingly, equation 2 represented the transfer coefficient for internal radial conduction. Application of relationship 6 to equations 2 and 3 yielded the resistance for internal radial conduction with a film. The coefficient for the internal circulation model was calculated by using equation 2, and the effective thermal diffusivity. This value and equation 4 yielded the overall resistance for internal circulation plus an appreciable film.

The observed overall coefficient was calculated from the relation

$$Q_e = U_e \cdot A \cdot \Delta t_m \tag{7}$$

The heat transferred from the dispersed phase was determined from

$$Q_e = M_d \cdot C_{p_d} \cdot \Delta t'_d \tag{8}$$

where

$$\Delta t'_d = \frac{\Delta t_d \times V_d}{109.3 \text{ cm.}} \tag{9}$$

The mean temperature difference (Δt_m) was evaluated by averaging the mean temperature differences calculated for unit lengths of the water bath. It was necessary to assume a linear plot for the dispersed phase temperature. A heat balance, see Appendix II, seemed to validate this assumption.

In order to perform the calculations it was necessary that the average drop diameter and velocity be known. The drop diameter was determined by measuring an appropriate number of drops and applying the statistical formula for the mean volume diameter (11)

$$d_v = \sqrt[3]{\frac{\Sigma\ nd^3}{\Sigma\ n}} \tag{10}$$

The drop velocity was calculated from the equations presented by Klee and Treybal (12). The equations are

$$v_1 = 38.3\ \rho_c^{-0.45} \cdot \Delta\rho^{0.58} \cdot u_c^{-0.11}\ d^{0.70} \tag{11}$$

and

$$v_{11} = 17.6\ \rho_c^{-0.55} \cdot \Delta\rho^{0.28} \cdot u_c^{0.10}\quad 0.18 \tag{12}$$

The critical diameter which determines transition from v_1 to v_{11} is calculated by

$$d_c = 0.33\ \rho_c^{-0.14} \cdot \Delta\rho^{-0.43} \cdot u_c^{0.30}\quad 0.24 \tag{13}$$

Although the comparison of the observed and the theoretical resistances identified the transfer mechanism, further analysis was required to explain the existance of the particular mechanism. A necessary part of this analysis was the calculation of the drag on the experimental drops; this was determined from the equation presented by Hughes and Gilliland (5).

$$\text{Drag} = C_D \text{ (Frontal Area) } (\rho_c \cdot V^2/2gc) \tag{14}$$

The drag coefficient, C_D , was calculated from either

$$Re_1 = 22.2\, C_D^{-5.18} \cdot We^{-0.159} \tag{15}$$

or

$$Re_{11} = 0.00418\, C_D^{2.91} \cdot We^{-1.81} \tag{16}$$

depending on the value of equation 13. Both equations 15 and 16 are the work of Klee and Treybal (12).

It was considered desirable to compare the experimental film coefficient with the film coefficient for mercury drops (7) and the coefficient for free convection (13).

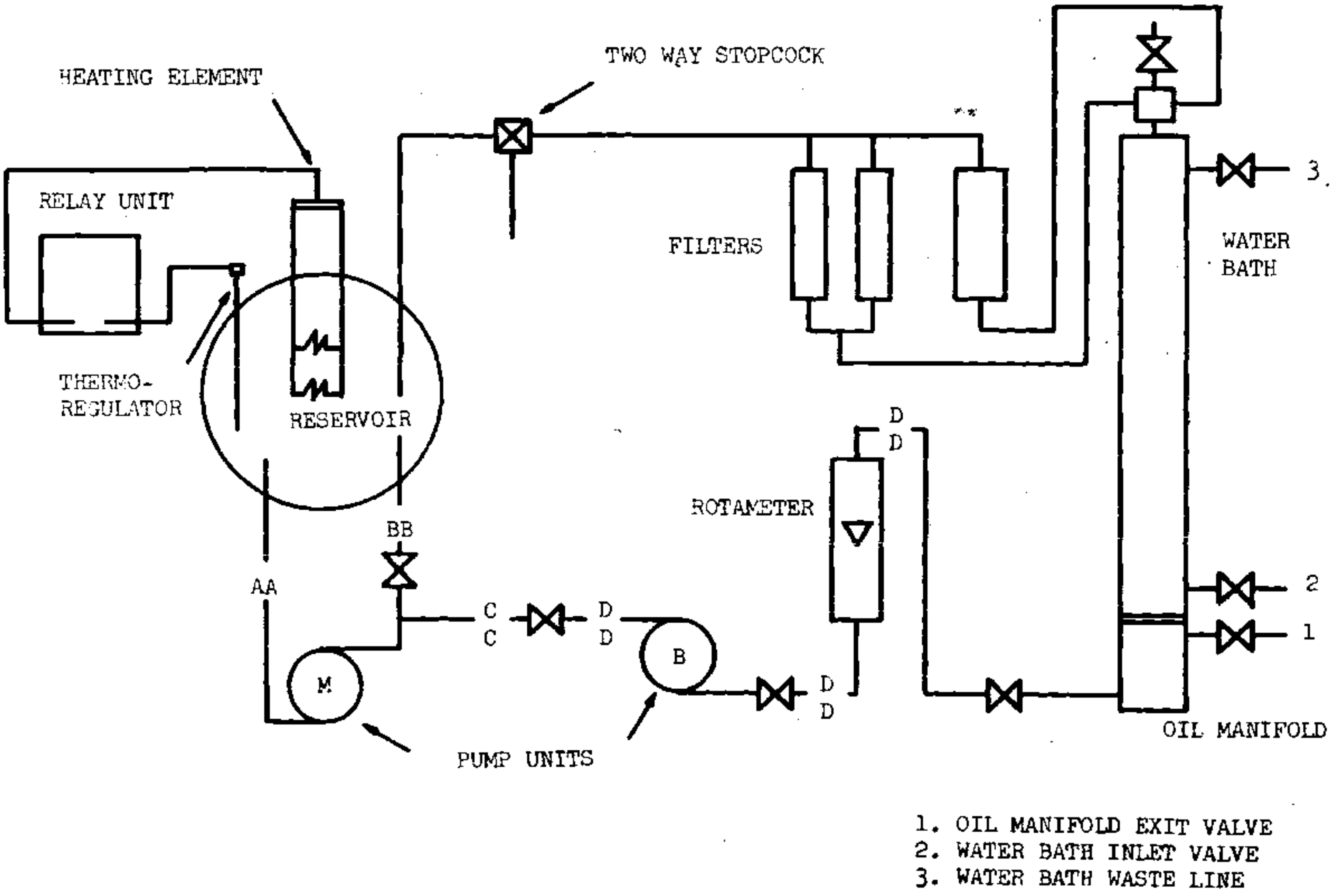


Figure 1. Experimental Setup

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

A sketch of the apparatus is shown in Figure 1. The equipment is most conveniently described by presenting it in functional groups. These groups are as follows: the constant temperature bath, the pumps and the piping system, the heat exchanger, the filters, and the auxiliary equipment.

The constant temperature bath.--This unit consisted of a reservoir, an immersed heating element, and a control system. A twelve gallon circular pyrex tank was used as the reservoir for the white mineral oil. The heating element contained a five hundred watt intermittent heater and a three hundred watt auxiliary heater. A microset thermoregulator, operating through a relay unit, controlled the heating element. The relay unit is a product of the Precision Scientific Company and has a catalogue number of 66535. A stirrer enabled the thermoregulator to control the average temperature of the bath.

The pumps and the piping system.--Two centrifugal pumps were required. The main circulating pump unit, marked M in Figure 1, was obtained from the Precision Scientific Company and has a catalogue number of 9040. The booster pump unit, marked B in Figure A, was obtained from Eastern Industries and has a designation of model E-1. The powerstat controlling the booster pump was supplied by the Superior Electric Company and is designated as type 116. In Figure 1, lines marked AA, BB, and CC were made from

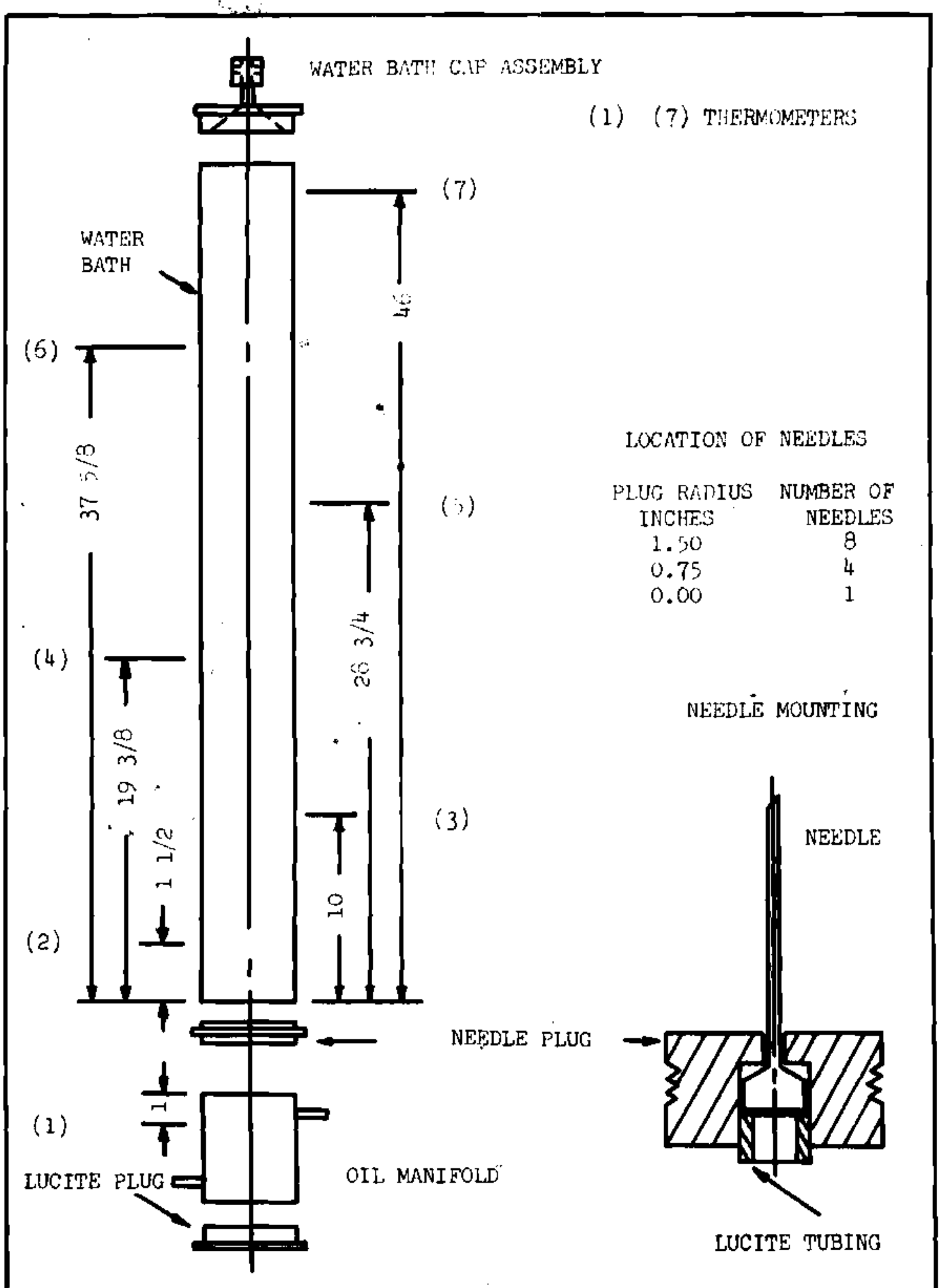


Figure 2. Exploded Sketch of Heat Exchanger

5/8 inch brass pipe. Lines marked DD were made from 1/2 inch brass pipe. The remaining lines were made of 1/2 inch Fisher plastic tubing. A rotameter was installed to permit visualization of the flow rate.

The heat exchanger.--This unit was constructed from a lucite column of fifty four inches in length, 1/8 inch in wall thickness, and 3-1/4 inches in inside diameter. The column was divided into two sections by the insertion of a one inch thick lucite plug mounted in a vertical position. The upper section was forty-eight and a half inches in length and was designated as the water bath. The lower section was five and a half inches in length and was designated as the oil manifold. The lucite plug, creating the division, was pierced by thirteen hypodermic needles. The needles were twenty gauge in diameter, one and a half inches in length, and made of stainless steel. Details of the needle emplacement are shown in Figure 2. The oil manifold was completed by sealing the bottom of the lower section with a one inch thick lucite plug. Two short lengths of 3/8 inch lucite tubing were fitted to the manifold to provide inlet and outlet lines. A lucite plug one inch in thickness and three inches in diameter was internally milled to a funnel shape, and then tapped at its center with a lucite tube 1/2 inch in diameter and seven inches in length. A lucite cross was attached to the end of this exit line. This assembly served as a cap for the water bath. The upper section was drilled to accommodate six thermometers and two sections of 3/8 inch lucite tubing. The positions of these holes and an exploded sketch of the complete unit are shown in Figure 2.

Filters.--Two filter units were required. One unit consisted of two pyrex tubes one and a half inches in diameter and twelve inches long. The second unit was a twelve inch drying tower. The units were mounted vertically, and filled to half their depth with pyrex glass filtering wool. Two inches of copper shot were poured on top of each bed of filtering wool. Inlet and outlet openings were plugged with rubber stoppers pierced by appropriate glass tubing. The exit lines from both units discharged to a single line which returned the oil to the constant temperature bath. A two way stopcock was installed in this common line to permit sampling.

Auxiliary equipment.--A du Nouy Tensiometer, four pycnometers, a thermometer calibrated by the National Bureau of Standards, and a Saybolt Viscosimeter were required for the determination of the physical properties of the mineral oil. The white mineral oil used in this experiment is sold under the trade name of Merusol by the Standard Oil Company of Kentucky.

A trip balance, twelve volumetric flasks, two Eastern Kodak timers, a 4 x 5 Speedgraphic camera, three tungsten lights, Eastman Kodak Royal-X pan film, and seven laboratory grade thermometers complete the apparatus required in this experiment.

CHAPTER III

EXPERIMENTAL PROCEDURE

Heat transfer measurements.--Twenty-four experimental runs were performed. The runs were divided into five groups. Each group, except one, was conducted at a particular temperature level and required five flow rates. The temperature levels were varied from 120° F through 200° F in 20° increments. The flow rates were set by using rotameter readings of 12, 14, 16, 18, and 20. At the 200° F level, the rotameter reading of 20 could not be attained.

Each run followed the same procedure. The constant temperature bath was set for the desired temperature level and allowed a warm up period. When the bath reached the desired temperature, the oil manifold was filled by starting pump unit M and opening the appropriate valves. The exit line from the oil manifold was allowed to remain open until the manifold reached a constant temperature. At that time, the manifold exit valve was closed and the water bath inlet valve opened. It was necessary to maintain the oil flow while filling the water bath. The water flow was stopped when the liquid level in the water bath reached the waste line. This line was held open until the emulsion, that formed during the filling of the bath, drained off. The cap assembly was placed in position and the return lines opened. The powerstat, controlling pump unit B, was turned on and adjusted to give the desired rotameter setting. As quickly as possible, the camera and tungsten lights were positioned and a photograph taken of the flow pattern. The camera was set at a lens opening of f 11 and a shutter speed of 1/200. The focus point of the photograph was the center of the water bath. The water bath was then wrapped with 1/8 inch thick asbestos sheets. An outside wrapping of aluminum foil completed the insulation. A Kodak timer was started and the recorded run commenced. All temperatures were read every three minutes, and a flow rate sample was taken every five minutes. This was accomplished by measuring the time required to collect the sample. The two way stopcock and a Kodak timer facilitated this operation. The runs were of one hour in duration or less, depending on the operating conditions. Shutdowns, other than for mechanical failures, were caused by either a rapid decrease in the efficiency of the filters or plugging of the hypodermic needles. This latter phenomenon may have been caused by small particles of lint or the needles may have been acting as filters for water contained in the oil. At the completion of a run, the camera and tungsten lights were repositioned and a photograph taken of the flow pattern.

Measurements of physical properties.--The density of the Merusol was calculated from pycnometer measurements. The viscosity was determined by the use of a Saybolt viscosimeter. A du Nouy Tensiometer was used to measure the interfacial tension. Tables of the viscosity, density, and interfacial tension are presented in Appendix III. A hydrometer and a standard equation (13) were used to determine the A. P. I. number of Merusol.

Measurement of globule diameter.--The mean volume diameter was used as the average diameter of the oil globules. This diameter was determined by measuring all the clearly defined bubbles in the photographs of the individual runs and applying equation 10. The variation of the bubble diameter is presented in Appendix II. A small meter stick was mounted on the side of the water bath while making the photographs, see Figure 3. It was hoped that this arrangement would lessen errors in measurement due to paralax.

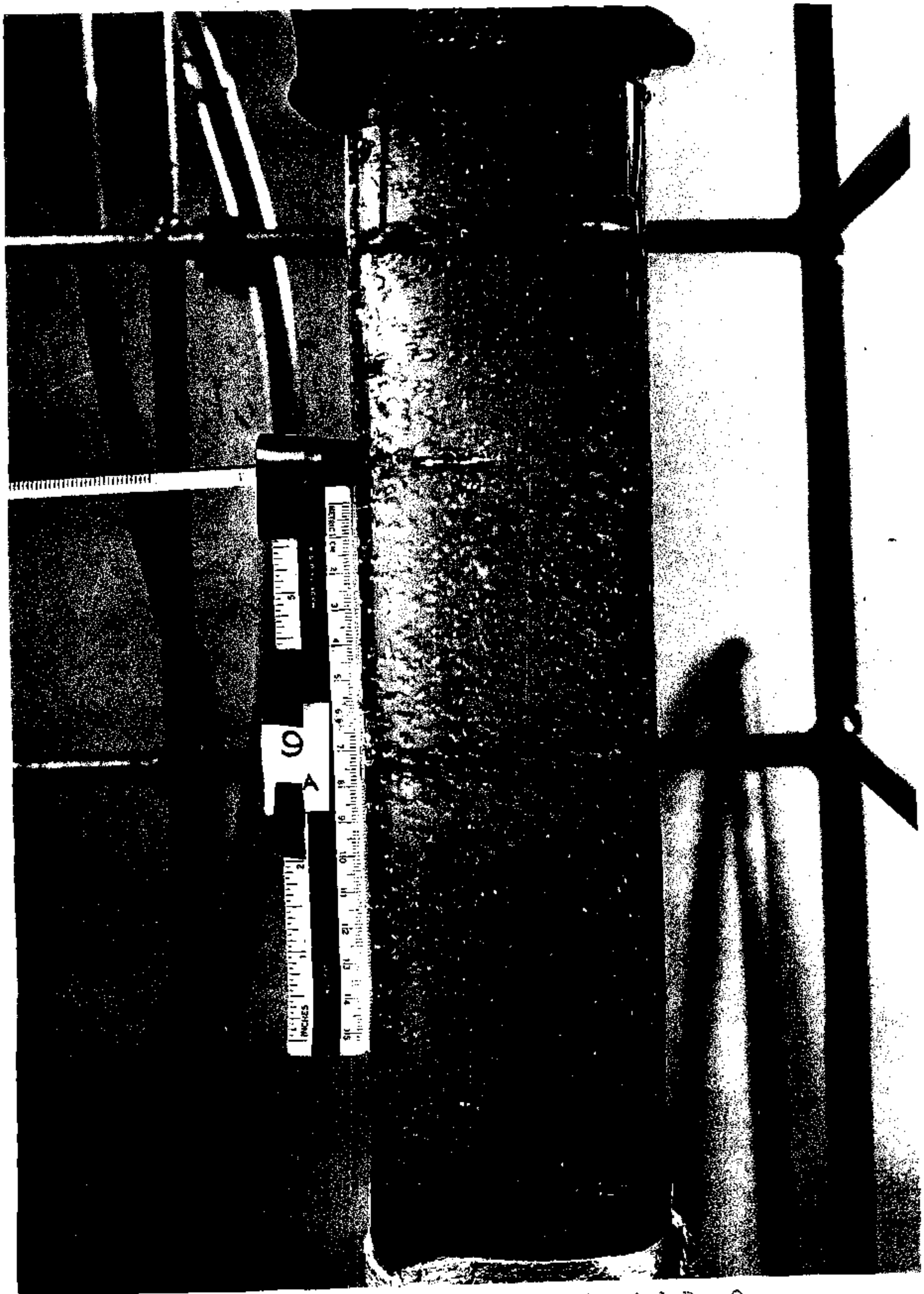


Figure 3. Photograph of Experimental Run 9

CHAPTER IV

DISCUSSION OF RESULTS

The data and calculated results are presented in Appendix IV and Appendix I.

Discussion of the transfer mechanism.--Table 1 presents the comparison of the observed transfer resistances, and the calculated resistances. Since the observed transfer resistances compare favorably with the transfer mechanisms having appreciable film resistances, it is assumed that a continuous phase film did exist about the experimental drops. Table 2 presents the comparison of transfer resistances having a film contribution, and the observed resistances. Acceptance of the values of the theoretical resistances creates two distinct shifts in transfer mechanisms; for a Reynolds number range of 530 to 990 the observed resistance values indicate a mechanism of internal circulation with an outside film, for a Reynolds number range of 530 to 350 the mechanism of radial conduction with an outside film is indicated, and for a Reynolds number of 350 to 280 the mechanism of internal circulation with an outside film is again intimated. This latter shift is doubted for two reasons:

1. It appears highly unlikely that the resistance for internal circulation would be greater than that for radial conduction; and

2. Once the viscous damping force hindering circulation has become effective, it does not seem probable that this force would be overcome while the skin friction continued to decrease.

Table 1. Comparison of Resistances

R_0 = observed resistance (sec.cm.^{2} $^\circ$C/cal.)

R_1 = resistance for radial conduction with no appreciable film.

R_2 = resistance for radial conduction with an outside film.

R_3 = resistance for internal circulation with no appreciable film.

R_4 = resistance for internal circulation with an outside film.

Run No.	R_0	R_1	R_2	R_3	R_4
1	110.98	155.00	165.48	139.84	143.16
2	231.32	217.86	226.10	186.18	190.40
3	433.75	272.10	279.54	291.97	295.96
4	408.16	276.47	283.72	299.31	303.26
5	255.91	226.39	234.75	194.47	198.71
6	173.67	194.70	203.82	159.38	163.81
7	172.83	206.91	215.75	165.31	169.67
8	231.97	222.17	230.37	194.55	198.76
9	293.39	242.00	249.80	226.20	230.29
10	195.01	214.22	222.74	170.88	175.15
11	230.27	233.26	241.37	203.54	207.70
12	278.49	240.15	247.94	213.49	217.59
13	330.78	254.58	262.09	254.18	258.58
14	398.67	279.09	286.26	310.07	314.00
15	345.37	265.60	272.13	273.00	276.95
16	294.37	240.78	248.44	223.31	227.36
17	313.07	252.33	259.88	238.32	242.35
18	330.41	252.58	259.83	256.08	260.03
19	334.75	255.42	262.78	259.87	263.84
20	391.29	275.10	282.27	296.91	300.83
21	398.42	276.31	283.31	305.90	309.77
22	464.27	303.58	310.40	362.05	365.87
23	398.43	282.64	289.66	312.79	316.66
24	428.22	287.60	294.42	340.83	344.66

Table 2. Comparison of Selected Resistances

Re = Reynolds number

R_o = observed resistance (sec.cm.^{2} ^oC/cal.)

R_2 = resistance for radial conduction with an outside film.

R_4 = resistance for internal circulation with an outside film.

Run No.	Re	R_2	R_o	R_4
1	990.83	165.48	110.98	143.16
7	694.7	215.75	172.83	169.67
6	664.5	203.82	173.67	163.81
10	594.2	222.74	195.01	175.15
2	529.2	226.10	231.32	190.40
8	503.9	230.37	231.97	198.76
12	459.2	247.94	278.49	217.59
11	443.1	241.37	230.27	207.70
5	441.0	234.75	255.91	198.71
16	440.6	248.44	294.37	227.36
18	398.7	259.83	330.41	260.03
17	384.4	259.88	313.07	242.35
9	382.5	249.80	293.39	230.29
13	351.8	262.09	330.78	258.58
15	346.3	272.13	345.37	276.95
19	359.5	262.78	334.75	263.84
21	324.3	283.31	398.42	309.77
20	314.0	282.27	391.29	300.83
23	307.4	289.66	398.43	316.66
24	300.6	294.42	428.22	344.66
14	298.7	286.26	398.67	314.00
4	292.7	283.72	408.16	303.26
3	289.2	279.54	433.76	295.96
22	280.4	310.40	464.27	365.87

The use of an effective thermal diffusivity in equation 2, for the calculation of the resistance for internal circulation, is therefore considered adequate only when the Reynolds number is greater than 350. Accordingly, for nineteen of the twenty-four experimental runs, the transfer mechanism is assumed to be that of radial conduction with an outside film resistance. The corresponding Reynolds numbers cover a range of 280 through 530. Figure 4, a plot of the observed resistances (R_o) and the resistances for radial conduction with a film (R_2), indicates the transition from solid sphere performance. Unfortunately the dispersed phase viscosity was beyond the boundaries of Garner's and Skelland's (3) plot, thus preventing a comparison of transitional Reynolds numbers.

The circulation effects could have been the results of either skin friction or drop oscillation. The latter phenomenon will cause both boundary layer degradation (7), and a unique circulation pattern (5). However, a comparison of the film coefficients, Table 3, indicates that the experimental film coefficient is less than the theoretical film coefficient for the runs accredited with internal circulation. This would seem to discount the existence of drop oscillation. Skin friction can be represented by the measurable quantity of the drag on the liquid drop. Figure 5 is a plot of the observed resistances, and the resistances for radial conduction with a film versus the experimental values of the drag. For increasing values of drag, there is a corresponding decrease in resistance and an eventual change in mechanism. The onset of the experimental circulation is therefore considered a result of skin friction rather than drop oscillation.

<u>Discussion of the film coefficients</u>.--Table 4 is a comparison of the ex-

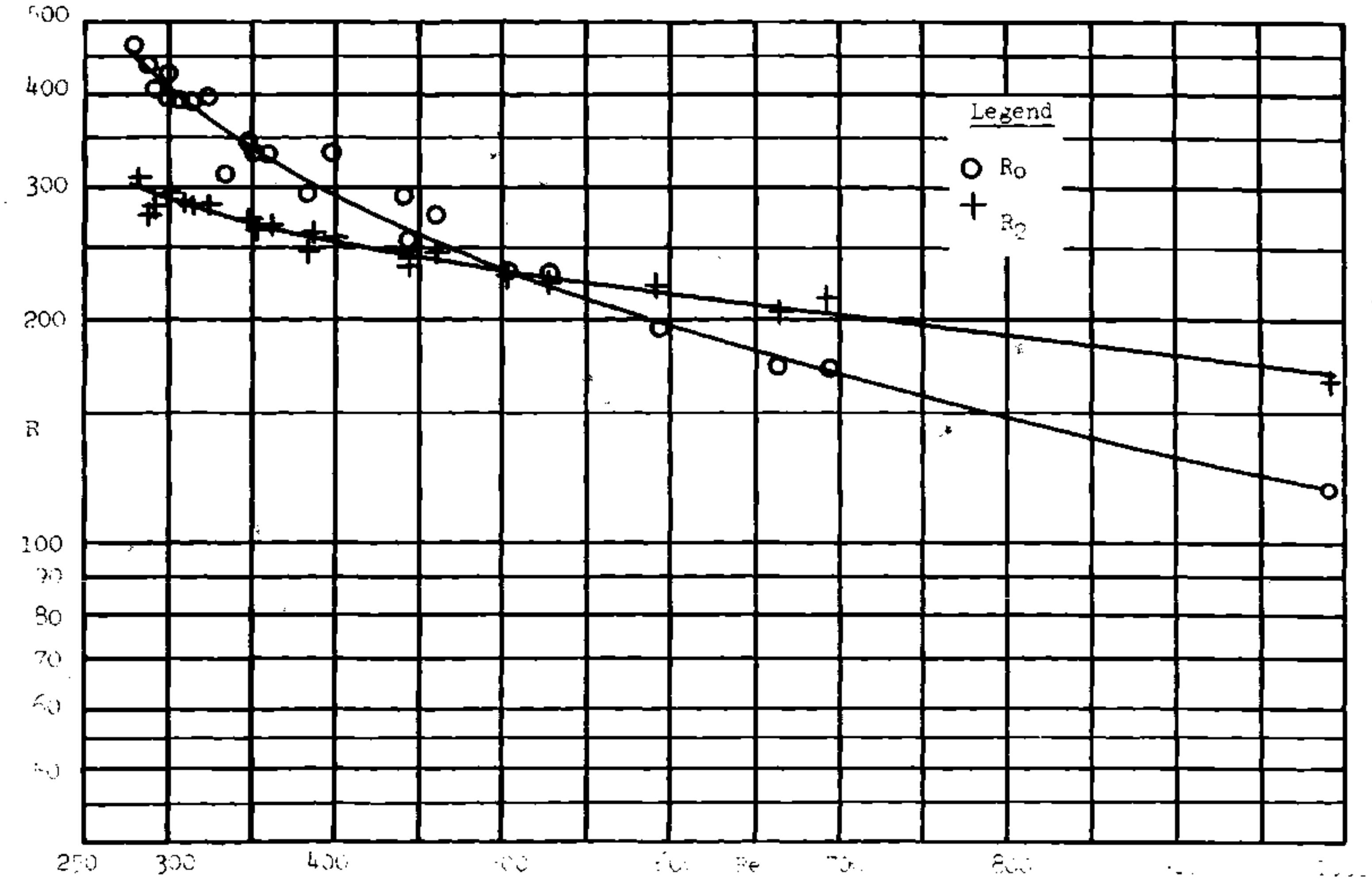


Figure 4. Resistances versus Reynolds Number

perimental film coefficients, the film coefficients from equation 3, the film coefficients from Figure 8, and the film coefficients for free convection from Figure 9. In contrast to the theoretical values, the experimental coefficients increase as the Reynolds numbers become larger. This increase may be a result of the corresponding increase in the drag. Fourteen of the nineteen are very small even when compared with the coefficients for free convection. This indicates either a deficiency in the mathematical analysis or perhaps an unusual effect at the interface of the drop.

Discussion of the transfer coefficient.--The overall transfer coefficient was improved by the shift in mechanism from radial conduction to internal circulation. This is in accord with the work of previous investigators (7, 8).

The major contribution to the overall resistance is the transfer coefficient for the dispersed phase (h_d). Therefore, it seems reasonable to postulate that for systems where the ratio of the viscosities of the dispersed and continuous phases is large, the controlling resistance will lie in the dispersed phase.

A direct measure of the decreased thermal resistance is the drag on the experimental drops. Therefore, for a transfer process involving a liquid drop rising through a continuous liquid phase, it appears desirable to obtain as large a value of drag as is practical.

Because of the limited data, no attempt could be made to perform a correlation by dimensional analysis. This seems reasonable when one considers the variables involved, which are the diameter of the drop; the densities, viscosities, and diffusivities of the two phases; the velocity

Table 3. Comparison of Film Coefficients

h_e = experimental film coefficient (cal./sec.cm^2 °C)

h_{c_2} = film coefficient for radial conduction mechanism

h_{c_4} = film coefficient for internal circulation mechanism

Run No.	h_{c_2}	h_{c_4}	h_e
1	0.0954	0.1978	
2	0.1214	0.2372	0.07429
3	0.1344	0.2505	0.00619
4	0.1379	0.2534	0.00759
5	0.1196	0.2359	0.03388
6	0.1097	0.2255	0.07000
7	0.1131	0.2294	0.13300
8	0.1219	0.2378	0.10204
9	0.1282	0.2242	0.01988
10	0.1174	0.2340	0.04140
11	0.1233	0.2405	0.03742
12	0.1283	0.2437	0.0261
13	0.1331	0.2501	0.01312
14	0.1395	0.2544	0.00836
15	0.1532	0.2531	0.01254
16	0.1306	0.2472	0.01866
17	0.1325	0.2482	0.01646
18	0.1379	0.2529	0.01285
19	0.1358	0.2520	0.01261
20	0.1395	0.2549	0.00861
21	0.1429	0.2584	0.00819
22	0.1466	0.2621	0.00622
23	0.1425	0.2582	0.00864
24	0.1467	0.2613	0.00711

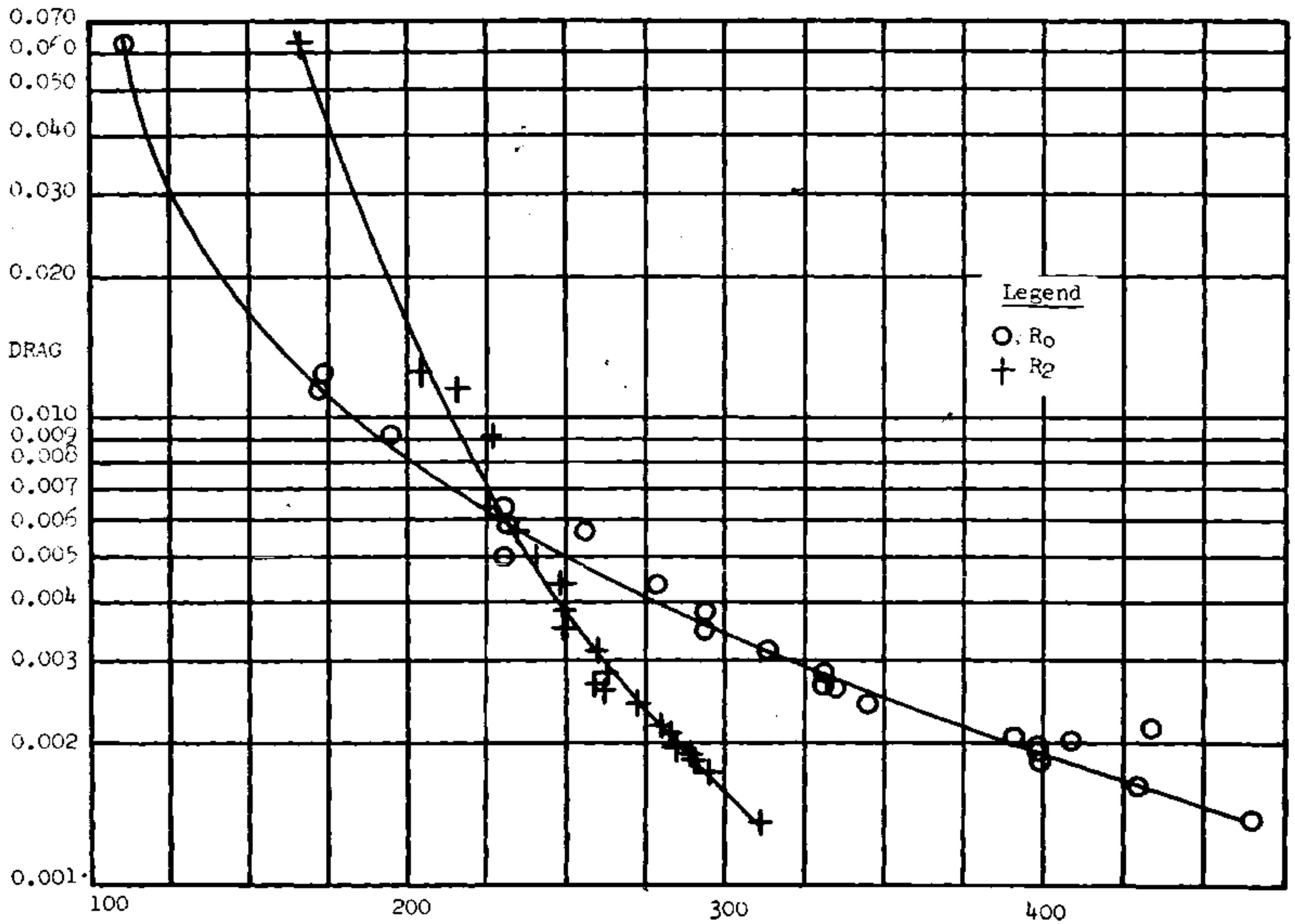


Figure 5. Resistances versus Drag

of the drop; the interfacial tension; and the transfer coefficient.

CHAPTER V

CONCLUSIONS

The conclusions resulting from the present investigation may be summarized as follows:

1. The heat transfer coefficient for a liquid drop rising through a continuous liquid phase will be improved by the onset of internal circulation within the drop.

2. For a transfer process involving a liquid drop rising through a continuous liquid phase it is desirable to obtain as large a value of drag as is practical.

3. If the ratio of the viscosities of the dispersed phase and the continuous phase is large, the controlling transfer resistance will lie in the dispersed phase.

CHAPTER VI

RECOMMENDATIONS

Since the experiment involved only one set of phases, it is difficult to explain the high resistances encountered at low Reynolds numbers. Therefore, it is suggested that the mathematical analysis should be tested with several sets of dispersed and continuous phases. It is recommended that a wide range of viscosities be represented by the selected phase sets.

APPENDIX I

CALCULATED DATA

Table 4. Comparison of Film Coefficients for a Solid Sphere

Re = Reynolds number

h_e = experimental film coefficient (cal./sec.cm^2 ^oC)

h_{c_2} = film coefficient from equation 3

h'_{c_2} = film coefficient from Figure 8

h_f = free convection coefficient from Figure 9

Run No.	Re	h_e	h_{c_2}	h'_{c_2}	h_f
1	990.83		0.0954	0.1306	0.01804
7	694.7		0.1131	0.1457	0.02156
6	664.5		0.1097	0.1408	0.01766
10	594.2		0.1174	0.1480	0.01283
2	529.2	0.07429	0.1214	0.1506	0.02236
8	503.9	0.10204	0.1219	0.1492	0.02229
12	459.2	0.0261	0.1283	0.1545	0.02422
11	443.1		0.1233	0.1489	0.02356
5	441.0	0.03388	0.1196	0.1433	0.02322
16	440.6	0.01866	0.1306	0.1571	0.02486
18	398.7	0.01265	0.1379	0.1610	0.02607
17	384.7	0.01646	0.1325	0.1546	0.02419
9	382.5	0.01988	0.1282	0.1493	0.02205
13	351.8	0.01312	0.1331	0.1536	0.02601
15	346.3	0.01254	0.1532	0.1572	0.02559
19	359.5	0.01261	0.1358	0.1502	0.02655
21	324.3	0.00819	0.1429	0.1609	0.03085
20	314.0	0.00861	0.1359	0.1569	0.02790
23	307.4	0.00864	0.1425	0.1593	0.03204
24	300.6	0.00711	0.1467	0.1624	0.03360
14	298.7	0.00836	0.1395	0.1554	0.02489
4	292.7	0.00759	0.1379	0.1530	0.02582
3	289.2	0.00619	0.1344	0.1495	0.02539
22	280.4	0.00622	0.1466	0.1615	0.03153

Table 5. Internal Coefficients for Solid Sphere and Circulating Drop Models

h = cal./sec.cm.^{2} ^{o}C

$h_{d_{1\ \&\ 2}}$ = internal coefficient for radial conduction mechanism

$h_{d_{3\ \&\ 4}}$ = internal coefficient for internal circulation mechanism

Run No.	$h_{d_{1\ \&\ 2}}$	$h_{d_{3\ \&\ 4}}$
1	0.00645	0.007242
2	0.00459	0.005371
3	0.003675	0.003425
4	0.003617	0.003341
5	0.004417	0.005142
6	0.005136	0.006274
7	0.004833	0.006049
8	0.004501	0.005190
9	0.003442	0.00442
10	0.004668	0.005852
11	0.004287	0.004913
12	0.004164	0.004684
13	0.003928	0.003928
14	0.003583	0.003225
15	0.003765	0.003663
16	0.004153	0.004478
17	0.003963	0.004196
18	0.003959	0.003905
19	0.003915	0.003848
20	0.003635	0.003368
21	0.003619	0.003269
22	0.003294	0.002762
23	0.003538	0.003197
24	0.003477	0.002934

Table 6. Dimensionless Groups Required for Calculations

Run No.	Re	Pr	We	Drag	C_D
1	990.83	4:74	2.07	0.0634	1.59
2	529.2	4.26	0.83	0.0064	0.683
3	289.2	4.24	0.36	0.00219	0.789
4	292.7	4.00	0.34	0.00202	0.788
5	441.0	4.74	0.74	0.00564	0.711
6	664.5	4.94	1.37	0.01250	0.644
7	694.7	4.52	1.33	0.01150	0.638
8	503.9	4.31	0.80	0.00599	0.690
9	382.5	4.21	0.53	0.00352	0.7385
10	594.2	4.51	1.08	0.00913	0.6975
11	443.1	4.42	0.69	0.00499	0.7110
12	459.2	3.96	0.64	0.00436	0.708
13	351.8	4.01	0.45	0.00281	0.7545
14	298.7	3.79	0.35	0.00190	0.7870
15	346.3	3.75	0.41	0.00241	0.7580
16	440.6	3.82	0.57	0.00380	0.7160
17	384.4	3.91	0.48	0.00313	0.7400
18	398:7	3.46	0.45	0.00267	0.73600
19	359.5	3.77	0.43	0.00261	0.7520
20	314.0	3.79	0.36	0.00207	0.7760
21	324.3	3.53	0.35	0.00194	0.7730
22	260.4	3.51	0.28	0.00137	0.8002
23	307.4	3.62	0.33	0.00183	0.7820
24	300.6	3.46	0.31	0.00162	0.7870

APPENDIX II

SAMPLE CALCULATIONS

These calculations are based on run number 9. Data are from Table 7 and Appendix III.

Drop diameter	=	0.2800cm.
Avg. temp. of the oil	=	45.71 °C
Avg. temp. of the water bath	=	41.72 °C
Temp. of inlet oil	=	50.73 °C
Temp. of outlet oil	=	41.28 °C
Flow rate, dispersed phase	=	3.167grms./sec.
Density of oil, ρ_d	=	0.8526grms./cm.^{3}
Specific heat of oil, C_{p_d}	=	0.4760grm.cal./grm. °C
Viscosity of oil, μ_d	=	0.277dyne sec./cm.^{2}
Thermal diffusivity of oil, α_d	=	0.0007738cm^2/sec.
Thermal conductivity of oil, k_d	=	0.00031295grm.cal./sec.cm. °C
Density of water, ρ_c	=	0.9916grms./cm.^{2}
Specific heat of water, C_{p_c}	=	0.9987grm.cal./grm. °C
Viscosity of water, μ_c	=	0.006356dyne sec./cm.^{2}
Interfacial tension, σ	=	41.20dynes/cm.
Thermal conductivity of water, k_c	=	0.001508grm.cal./sec.cm. °C

Calculation of Critical Diameter

$$d_c = (0.33)\ \rho_c^{-0.14} \times \Delta\rho^{-0.43} \times \mu_c^{0.30} \times \sigma^{0.24}$$

$$d_c = \left(0.33\frac{\text{sec.}^3}{\text{cm}^2}\right)\left(0.9916\frac{\text{grms.}}{\text{cm}^2}\right)^{-0.14}\left(0.1390\frac{\text{grms.}}{\text{cm}^3}\right)^{-0.43}\left(0.006356\frac{\text{dyne.sec.}}{\text{cm}^2}\right)^{0.30}\left(41.20\frac{\text{dynes.}}{\text{cm.}}\right)^{0.24}$$

$$d_c = 0.4130 \text{ cm.}$$

Calculation of Velocity

$$V_1 = 38.3\ \rho_c^{-0.45} \cdot \Delta\rho^{0.58} \cdot \mu_c^{-0.11} \cdot d^{0.70}$$

$$V_1 = \left(38.3\frac{\text{grm.}}{\text{sec.}^2\text{cm}}\right)\left(0.9920\frac{\text{grms.}}{\text{cm}^3}\right)^{-0.45}\left(0.1390\frac{\text{grms.}}{\text{cm}^3}\right)^{0.58}\left(0.006356\frac{\text{grm.}}{\text{sec.cm.}}\right)^{-0.11}\left(0.2800\text{cm.}\right)^{0.70}$$

$$V_1 = 8.75 \text{ cm./sec.}$$

Heat Transferred to Water Bath

$$Q = M_d \cdot C_{p_d} \cdot \Delta t_d$$

$$Q = (3.167 \text{ grms.}) \left(0.4760 \frac{\text{grm.cal.}}{\text{grm. }^{\circ}\text{C}}\right) \left(\frac{9.02\ ^{\circ}\text{C} \times 8.75 \text{cm./sec.}}{109.3 \text{ cm.}}\right)$$

$$Q = 1.089 \frac{\text{grm.cal.}}{\text{sec.}}$$

Calculation of the Mean Temperature Difference

Figure 7, $\sum \Delta t_m$ 47.882 C, Δt_m calc. for one second periods

Avg. Δt_m	=	3.99 °C
Avg. Oil Temp.	=	45.71 °C
Avg. Bath Temp.	=	41.72 °C
Avg. temp. difference	=	3.99 °C

Calculation of the Number of Drops

$$W_d \ \frac{\text{grms.}}{\text{sec.}} \cdot \frac{1}{\rho_d} \ \frac{\text{cm3}}{\text{grm.}} = \text{cm}^3/\text{sec.}$$

$$(3.167)\left(\frac{1}{0.8526}\right) = 3.719 \ \text{cm}^3/\text{sec.}$$

$$\text{Volume of drops} = \frac{1}{6} \pi d^3 = \frac{1}{6} \cdot \pi \ (0.2800)^3$$

$$= 0.01148 \ \text{cm}^3/\text{drop}$$

$$\text{Surface area of drops} = \pi d^2$$

$$= 0.2461 \ \text{cm}^2/\text{drop}$$

$$\text{Number of drops} = 3.719 \ \text{cm}^3/\text{sec.} \cdot \text{drop.}/0.01148 \ \text{cm}^3$$

$$= 324 \ \text{drops/sec.}$$

Calculation of Experimental Coefficient

$$Q = U_E \cdot A \cdot \Delta t_m$$

$$U_E = \frac{1.089 \text{ grm.cal./sec.}}{(324\text{drops})(0.2461\frac{\text{cm}^2}{\text{drop}})(3.99^\circ\text{C})} = 0.00342 \quad \frac{\text{grm. cal.}}{\text{sec.cm}^2\,{}^\circ\text{C}}$$

Calculation of Coefficient for Radial Conduction with no Appreciable Film

$$\frac{Q_1 \; r_1}{k_d \; A_1(t_i - t_o)} = 2\sum_{n=1}^{\infty} e^{-(n\pi)^2\theta}$$

$$\theta = \frac{\alpha}{r_1^2} \cdot T \quad \frac{0.0007738\text{cm}^2/\text{sec.}}{(0.1400)^2 \text{ cm}^2} \; (1 \text{ sec.})$$

$$\theta = 0.0394$$

From Figure 6, $$k_d \cdot A \cdot \frac{Q_1 \; r_1}{(t_i - t_o)} = 1.85$$

$$h_d = \frac{(k_d)(1.85)}{r_1} = \frac{(0.00031295)(1.85)}{0.1400} = 0.004140 \ \frac{\text{cal.}}{\text{sec.cm}^2 \ {}^oC}$$

$$\frac{1}{U_d} = \frac{1}{h_d} = R = \frac{1}{0.004140} = 242.0, \ R_1 = 242.00 \ \frac{\text{sec.cm}^2 \ {}^oC}{\text{cal.}}$$

Calculation of Coefficient for Radial Conduction with an Outside Film.

$$Nu = 2.0 + 1.3(Pr)^{0.15} + 0.66(Pr)^{0.31} \cdot (Re)^{0.50}$$

$$Pr = \frac{C_{p_c} \cdot \mu_c}{k_c} = \frac{(0.9987 \frac{\text{grm.cal.}}{\text{grm.} \ {}^oC})(0.006356\text{dyne.sec./cm})}{(0.001508\text{grm.cal./sec.cm.} \ {}^oC)}$$

$$Pr = 4.21$$

$$Re = \frac{d.v.\,\rho_c}{\mu_c} = \frac{(0.2800\text{cm.})(8.75\text{cm/sec.})(0.9916\text{grms./cm}^2)}{(0.006356\text{dyne.sec./cm}^2)}$$

$$Re = 382.5$$

$$\frac{dhc}{k_c} = 2.0 + 1.3(4.21)^{0.15} + 0.66(4.21)^{0.31} \cdot (382.5)^{0.50}$$

$$h_c = (23.80)\,\frac{(0.001508\text{ grm.cal./sec./cm }^oC)}{(0.2800\text{cm})}$$

$$h_c = 0.1282\text{ cal./sec. cm}^2\ ^oC$$

$$\frac{1}{U_2} = \frac{1}{h_c} + \frac{1}{h_d} = R_2 = \frac{1}{0.1282} + \frac{1}{0.00414} = 7.80 + 242.0 = R_2 = 249.80\frac{\text{sec.cm}^2\ ^oC}{\text{cal.}}$$

Calculation of Coefficient for Internal Circulation with no Appreciable Film

$$\frac{Q\, r_1}{k_d\, l\,(t_i - t_o)} = 2 \sum_{n=1}^{\infty} \quad -(n\pi)^2\theta$$

$$\theta = \frac{\alpha}{r_1^2} \cdot \quad T = \frac{(0.0007738\text{cm}^2/\text{sec.})\ (2.25)}{(0.1400)^2\ \text{cm}^2}\ (1\ \text{sec.})$$

$$\theta \doteq 0.0086$$

From Figure 6, $\dfrac{Q\, r_1}{k_d \cdot A_1\,(t_i - t_o)} = 0.88$

$$h_d = \frac{(0.88)(k_1)(2.25)}{(r_1)}$$

$$h_d = \frac{(0.88)(0.00031295\ \text{cal./sec/cm.}\ {}^{\circ}\text{C})(2.25)}{(0.1400\ \text{cm.})}$$

$$h_d = 0.00442 \text{ cal./sec.cm}^2 \, {}^\circ C$$

$$\frac{1}{U_3} = \frac{1}{h_d} = R_3 = \frac{1}{0.00442} = 226.2$$

$$R_3 = 226.2 \, \frac{\text{sec.cm}^2 \, {}^\circ C}{\text{cal.}}$$

Calculation of Coefficient for Internal Circulation with an Appreciable Film

$$Nu_c = 1.13 \sqrt{Pe_c} = 1.13 \cdot \sqrt{\frac{dVc}{\alpha c}}$$

$$Nu_c = 1.13 \sqrt{\frac{(0.2800\text{cm.})(8.75\frac{\text{cm.}}{\text{sec.}})(0.9987\frac{\text{grm.cal.}}{\text{grm. } {}^\circ C})(0.9916\text{grm/cm}^3)}{(0.001508 \frac{\text{cal.}}{\text{sec.cm. } {}^\circ C})}}$$

$$h_c = 1.13 \cdot 40.15 \cdot \frac{0.001508 \text{ cal/sec.cm } {}^\circ C}{0.2800 \text{ cm.}}$$

$$h_c = 0.2442 \text{ cal./sec.cm}^2\ {}^{\circ}C$$

$$\frac{1}{U_4} = \frac{1}{h_c} + \frac{1}{h_d} \therefore R_4 = \frac{1}{0.2442} + \frac{1}{0.00442} = 4.09 + 226.2$$

$$R_4 = \underline{230.29} \quad \frac{\text{sec.cm}^2\ {}^{\circ}C}{\text{cal.}}$$

Calculation of Experimental Film Coefficient.

	R (sec.cm^2 $^{\circ}$C/cal.)
Observed	292.39
R_1	242.00
R_2	249.80
R_3	226.2
R_4	230.29

$$R_c = \frac{1}{h_c} + \frac{1}{h_d} = \frac{1}{h_c} + 242.0 = 292.39$$

$$\therefore \frac{1}{h_c} = 50.39$$

$$h_c = 0.01988 \text{ cal./sec.cm}^2 \, {}^{o}C$$

Comparison of Film Coefficients

			h cal./sec.cm^2 ^{o}C
Experimental		h_e	= 0.01988
Equation	3	h_{c_2}	= 0.1282
Figure	8	h'_{c_2}	= 0.1430
Figure	9	h_c	= 0.02205

Calculation of the Drag

$$\text{Drag coefficient} = C_D = \text{Drag} \;/\; (\text{Frontal Area})(\rho_c v^2/2gc)$$

Also

$$C_D = \left[22.2 \;/\; Re \;.\; We^{0.169}\right]^{\frac{1}{5.18}}$$

$$C_D = \left[\frac{22.2}{(382.5)(0.00053)} \;\; 0.169\right]^{\frac{1}{5.18}}$$

$$C_D = (0.2080)^{0.193} = \underline{0.7385}$$

$$\text{Drag} = (C_D)(1/2 \text{ surface area})\left(\frac{\rho c v^2}{2gc}\right)$$

$$= \frac{(0.7385)(0.1230\text{cm}^2)(0.9916\text{grms/cm}^3)(8.75)^2\text{cm}^2/\text{sec}^2}{(2)(980\text{grms. cm./sec}^2)}$$

$$\text{Drag} = \frac{(0.7385)(0.1230)(0.9916)(76.6)}{(1960)} = \underline{0.00352}$$

Estimation of Dispersed Phase Temperature Profile

Run No.	Thermometer No. 2	and 3	t_c 4	Increase 5	6	^{o}C/sec. X
9.6						
9.12	1.51	1.21	1.82	1.28	1.18	1.35
9.18	1.01	1.01	1.01	1.09	1.19	1.20
9.24	1.04	1.01	0.73	1.21	1.03	0.80
9.30	0.74	1.02	1.34	0.71	1.03	1.20
9.36	0.83	0.81	0.73	1.01	0.84	0.90
9.42	0.82	0.90	0.93	0.71	0.89	0.85
9.48	0.72	0.51	0.62	0.91	0.66	0.65
9.54	0.41	0.83	1.03	0.40	0.76	0.75
9.60	0.81	0.50	0.20	0.55	0.82	0.30
	7.89	7.80	8.41	7.87	8.40	8.00
$\frac{\sum {}^{o}C}{10x360sec.}$ =	0.00243	0.0024	0.00259	0.00242	0.00257	0.00246

Avg. temp. increase of bath $= 0.00248\ {}^{\circ}C/sec.$

$$\text{Vol. of bath} = \pi r^2 L = \pi\ (17.02 cm^2)(L cm.) = 53.50\ L\ cm^3$$

$$M_c = \pi r^2 L \cdot \rho_c = 53.50 L \cdot \rho_c \quad (grms.)$$

$$M_c\ (grms.) \cdot C_{p_c}\ \frac{(grm.cal.)}{grm.\ {}^{\circ}C} \cdot \Delta t_c\ {}^{\circ}C = M_d (grms.) \cdot C_{p_d}\ \frac{(grm.cal.)}{grm.\ {}^{\circ}C} \cdot \Delta t_d\ {}^{\circ}C$$

$$53.50 \cdot 114.3 \cdot 0.9916 \cdot 0.9987 \cdot 0.00248 = 3.167 \cdot 0.4760 \cdot \Delta t_d$$

$$\frac{15.04}{(3.167)(0.4760)} = \Delta t_d = 9.98\ {}^{\circ}C$$

$$\text{experimental}\ \Delta t_d = 9.45\ {}^{\circ}C$$

$$Q_c = 53.50 cm^2 \cdot 8.75 \frac{cm.}{sec.} \cdot 0.9987 \frac{grm.cal.}{grm.\ {}^{\circ}C} \cdot 0.9916 \frac{grms.}{cm^3}$$

$$Q_c = 463.50 \frac{\text{grm.cal.}}{\text{sec.}}$$

<u>Heat balance</u>

$$463.50 \frac{\text{grm.cal.}}{\text{sec.}} = M_d \cdot C_{p_d} \cdot \Delta t'_d$$

For t_d range of 50.73 to 41.28, $\Delta t'_d$ will very from 0.75-77 $^\circ C/sec.$

From linear plot (fig. 7), the dispersed phase $\Delta t_d = 0.722\,^\circ C/sec.$

Since there is a discrepencency of 53 $^\circ C$ in our heat balance, a correction factor may be applied

$$\frac{0.53^\circ C \cdot 8.75 \text{cm./sec.}}{109.3 \text{ cm.}} = 0.0424\ ^\circ C/\text{sec.},$$

then

$$\Delta t'_d - 0.04 = 0.71 - 0.72\ ^{o}C/sec.$$

Therefore, it seems reasonable to use a linear plot for the dispersed phase.

Calculation of Transfer Coefficient for Internal Circulation, Equation 5

$$Nu_d = 0.00375\ Pe_d^{1}$$

$$h_d = 0.00375 \cdot \frac{dv}{\alpha} \cdot \frac{1}{1+\mu_d/\mu_c} \cdot \frac{k_d}{d}$$

$$h_d = 0.00375 \cdot \frac{8.75 cm/sec.}{0.0007738 cm^2/sec.} \cdot \frac{0.00031295 cal./sec.cm\ ^{o}C}{1 + \frac{0.277}{0.006356}}$$

$$h_d = 0.000298\ cal./sec.\ cm^2\ ^{o}C$$

$$\frac{1}{h_d} = R_{d_{3and4}} = 3350\ \frac{sec.cm^2\ ^{o}C}{cal.}$$

Table 7. Average Properties Required for Calculations

Run No.	d cm.	d_c cm.	V cm/sec.	td °C/sec.	Avg. Oil °C	Avg. Bath °C	t_m °C
1	0.5850	0.4289	12.10	1.207	41.17	35.91	5.26
2	0.3405	0.4140	10.07	1.075	46.88	41.16	5.72
3	0.2381	0.4140	7.84	0.854	47.33	41.37	5.96
4	0.2312	0.4049	7.76	0.880	49.86	44.23	5.63
5	0.2365	0.4313	9.65	1.301	43.17	35.86	7.31
6	0.4282	0.4507	11.52	1.086	39.35	33.94	5.41
7	0.4145	0.4220	11.48	1.411	44.84	38.04	6.80
8	0.3335	0.4165	9.90	1.091	46.17	40.47	5.70
9	0.2800	0.4130	8.75	0.724	45.71	41.72	3.99
10	0.3750	0.4160	10.82	1.823	47.23	38.22	9.01
11	0.3122	0.4151	9.51	1.356	46.83	39.24	6.59
12	0.2995	0.4029	9.30	1.078	50.99	44.89	6.10
13	0.2572	0.4029	8.41	1.197	51.02	44.11	6.91
14	0.2262	0.3936	7.71	0.703	51.41	47.11	4.30
15	0.2448	0.3951	8.18	0.973	53.26	47.66	5.60
16	0.2849	0.3951	9.08	1.077	52.72	46.57	6.15
17	0.2676	0.4013	8.62	0.913	50.71	45.52	5.19
18	0.2540	0.3886	8.43	1.006	57.99	52.20	5.79
19	0.2512	0.4292	8.32	1.171	54.07	47.35	6.72
20	0.2328	0.3959	7.88	1.231	54.64	47.01	7.63
21	0.2263	0.3880	7.85	1.197	58.34	50.95	7.39
22	0.2070	0.3853	7.38	1.377	60.31	51.22	9.09
23	0.2228	0.3899	7.72	1.425	58.31	49.66	8.65
24	0.2135	0.3837	7.56	1.652	62.60	52.18	10.42

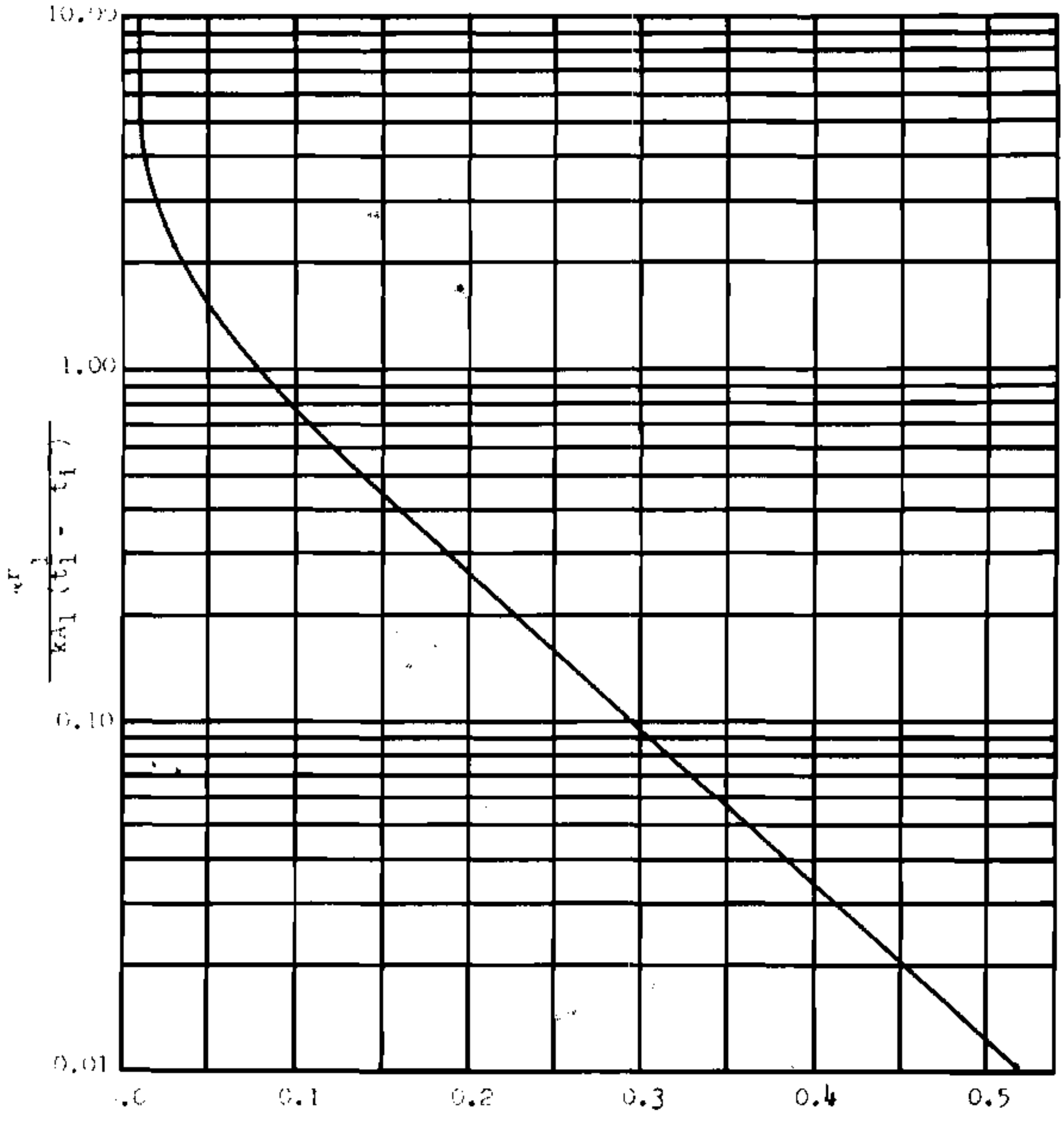
Table 8. Average Phase Conditions used in Calculations

Run No.	2	3	4	5	6	X	Outlet Oil °C	Inlet Oil °C	Flow Rate
1	36.22	36.25	35.90	35.77	35.72	35.79	35.95	47.35	1.629
2	41.52	41.64	41.20	40.92	40.94	40.81	41.08	53.29	2.228
3	41.85	41.73	41.53	41.15	41.07	40.88	41.47	53.93	2.820
4	44.92	44.78	44.42	43.94	43.81	43.56	43.72	56.71	5.884
5	36.07	36.06	35.99	35.74	35.72	35.62	35.86	51.29	1.860
6	34.19	34.25	33.93	33.86	33.83	33.72	34.25	45.03	1.484
7	38.35	38.41	38.05	37.86	37.88	37.76	38.19	52.25	2.153
8	40.90	40.80	40.42	40.00	40.06	39.89	40.16	52.76	2.853
9	42.52	42.18	41.85	41.37	41.33	41.21	41.28	50.73	3.167
10	38.85	38.64	38.42	37.89	37.82	37.63	38.08	57.38	4.009
11	39.29	39.67	39.47	39.98	39.01	38.80	39.12	55.44	2.054
12	45.42	45.39	45.00	44.61	44.56	44.43	44.71	57.96	2.816
13	45.40	44.96	44.07	43.50	43.52	43.24	43.26	59.63	3.420
14	48.00	47.82	47.29	46.71	46.54	46.13	46.46	56.91	3.270
15	48.79	48.42	47.89	47.26	46.95	46.63	46.80	60.41	3.994
16	47.27	47.06	46.56	46.18	46.18	45.91	46.28	59.80	2.339
17	46.20	46.22	45.62	45.04	44.99	44.75	44.97	57.06	2.780
18	53.28	52.94	52.46	51.78	51.57	51.23	51.54	65.17	3.492
19	48.81	48.50	47.43	46.76	46.46	46.20	46.41	62.53	3.615

(continued)

Table 8. Average Phase Conditions used in Calculations

Run No.	2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate
20	48.07	47.93	47.19	46.41	46.30	46.08	46.17	64.06	2.911
21	52.05	51.67	51.22	50.49	50.10	49.88	50.09	67.55	3.208
22	52.89	52.19	51.44	50.63	50.09	49.83	50.20	71.56	3.877
23	51.67	50.93	49.85	48.79	48.50	48.21	48.27	69.36	4.293
24	54.47	53.92	52.02	51.31	50.91	50.68	50.71	75.73	4.617



$$\theta = \frac{\alpha}{r_1^2} \cdot T$$

Figure 6. Plot of Equation 1

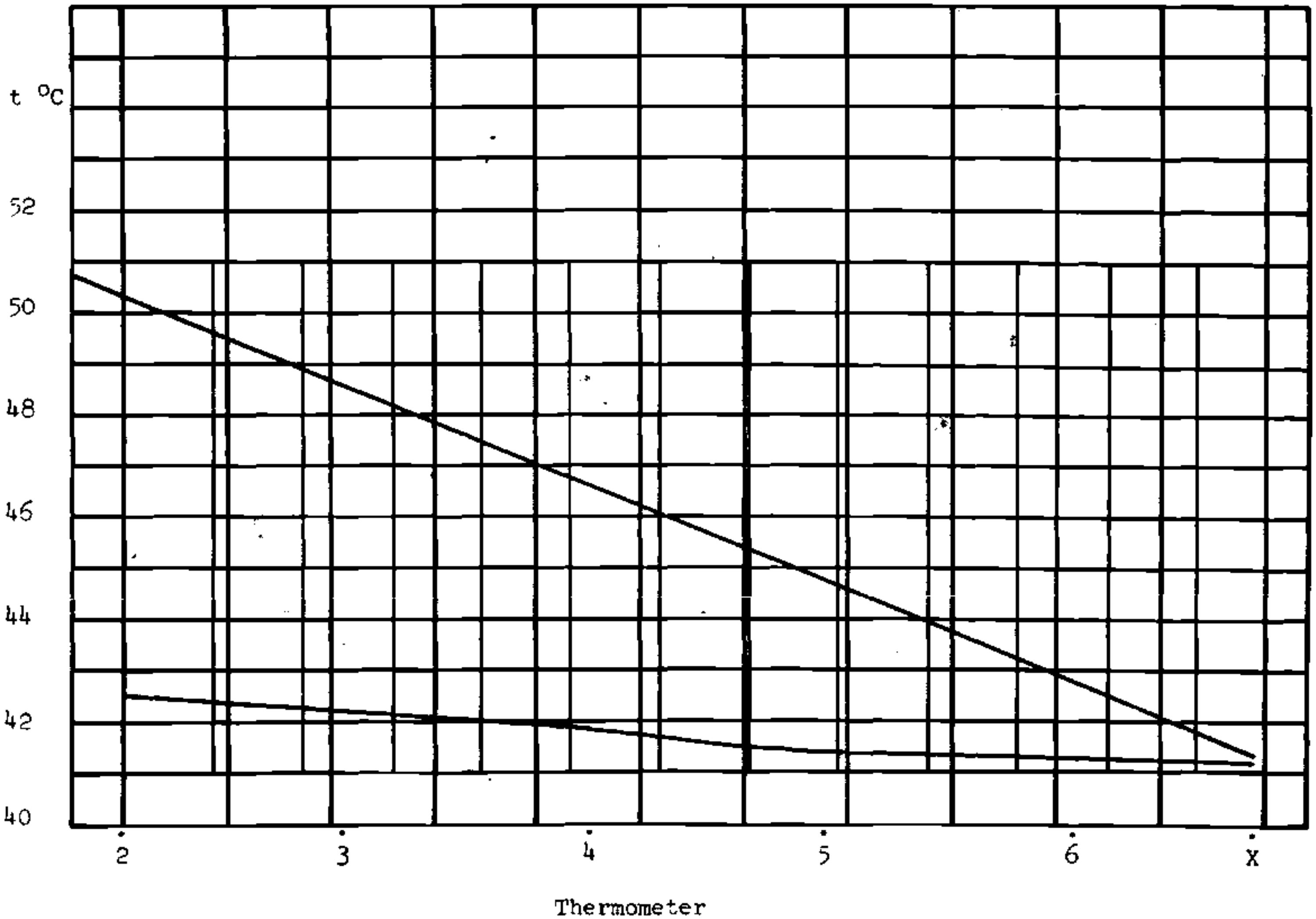


Figure 7. Phase Temperatures, Run no. 9

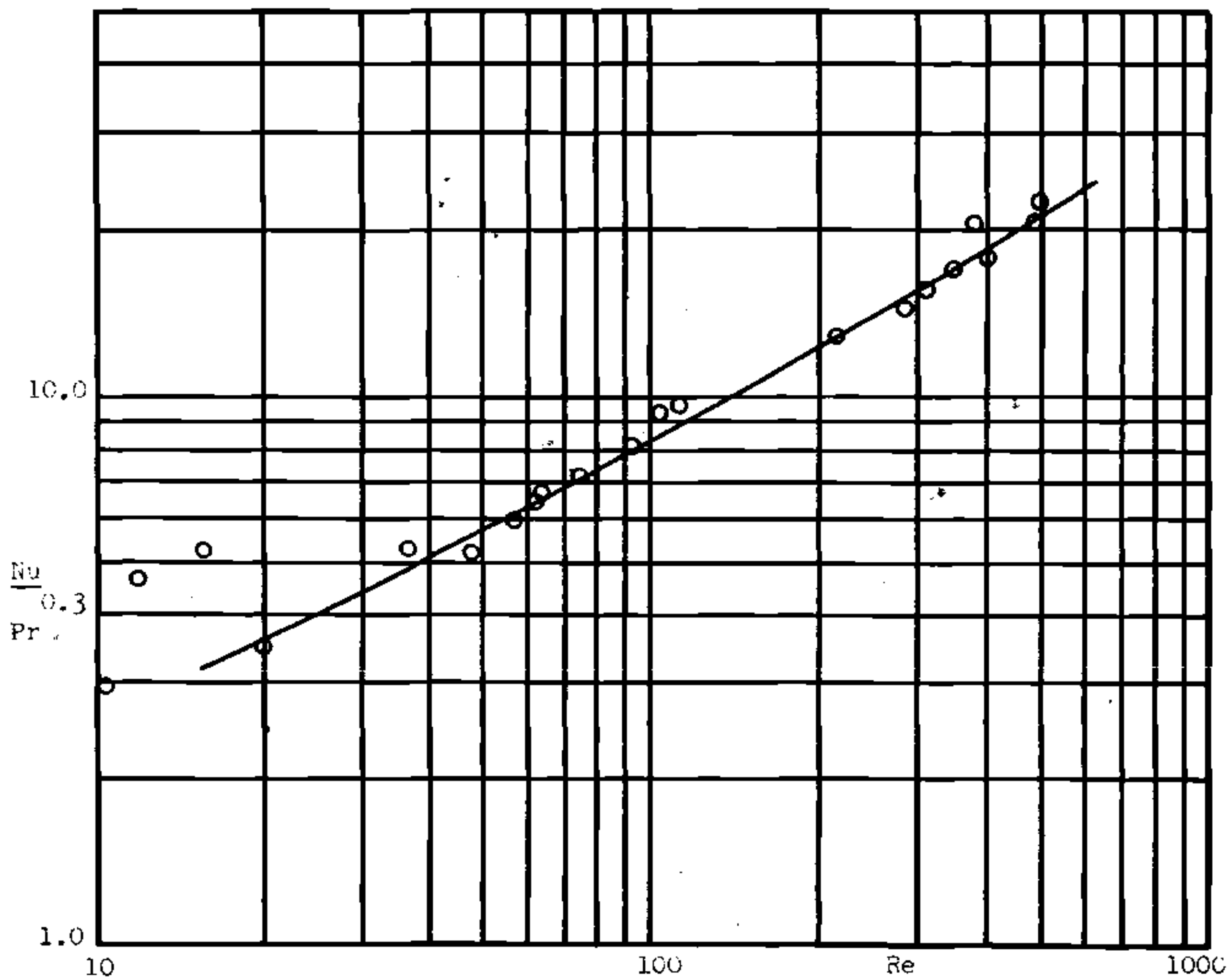


Figure 8. Film Coefficient for Mercury Drops

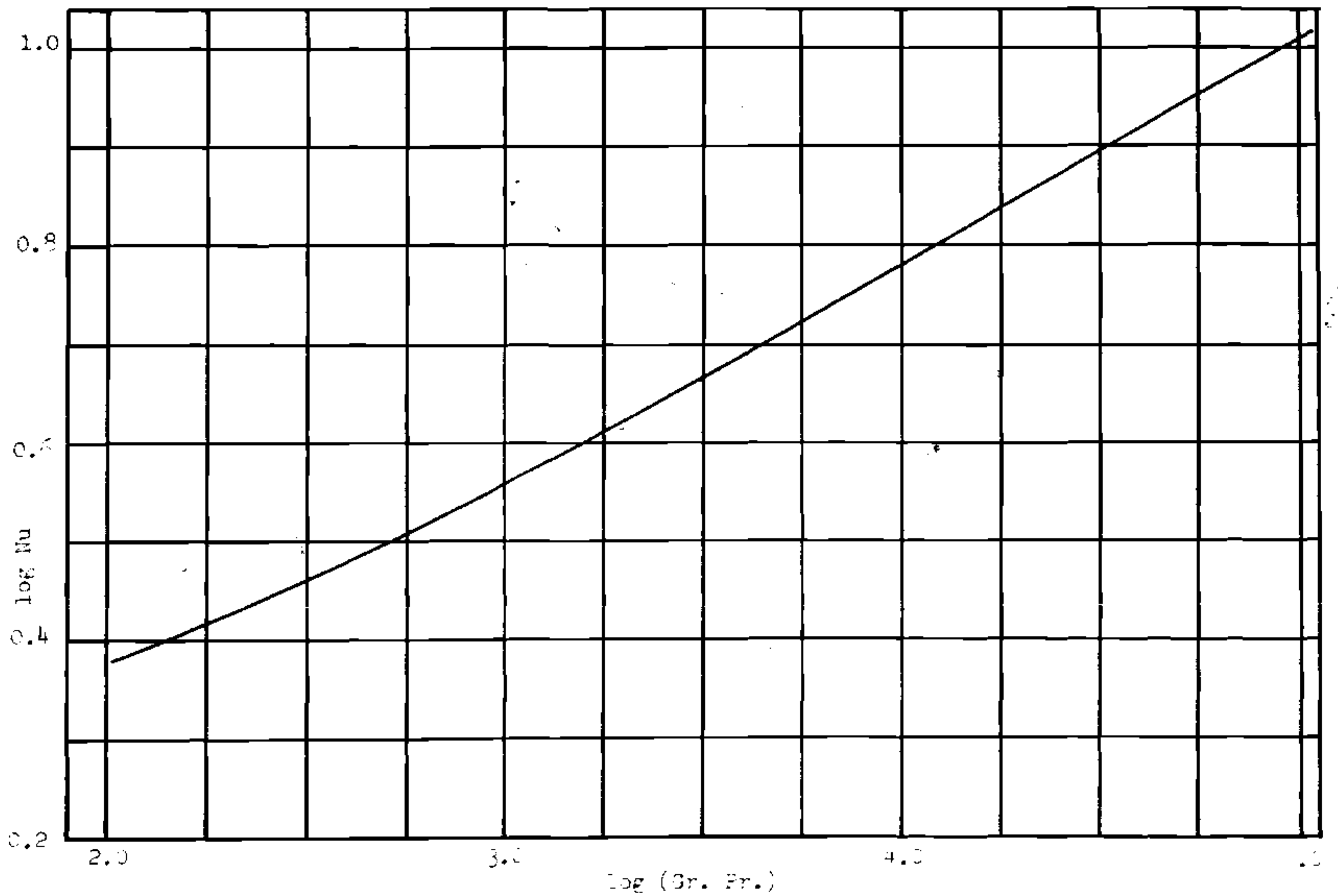


Figure 9. Film Coefficients for Free Convection

APPENDIX III

PHYSICAL PROPERTIES OF THE PHASES

Table 9. Physical Properties of Merusol

Temp. °C	k $\times 10^4$	C_p	α $\times 10^4$
36	3.1488	0.4685	7.820
38	3.1445	0.4698	7.807
40	3.1405	0.4711	7.792
42	3.1368	0.4727	7.775
44	3.1328	0.4745	7.758
46	3.1285	0.4763	7.735
48	3.1245	0.4782	7.710
50	3.1205	0.4800	7.685
52	3.1165	0.4822	7.655
54	3.1122	0.4840	7.628
56	3.1080	0.4860	7.595
58	3.1040	0.4882	7.560
60	3.1000	0.4900	7.528
62	3.0960	0.4920	7.490
64	3.0920	0.4942	7.455
66	3.0880	0.4962	7.420
68	3.0838	0.4982	7.382
70	3.0800	0.5000	7.345

k = grm.cal./sec.cm °C

C_p = grm.cal./grm. °C

α = cm^2/sec.

The values of the thermal conductivity and the specific heat were determined from the literature (15).

Table 10. Physical Properties of Merusol and of Water

Temp. °C	σ	μ	ρ
36	42.62		0.8583
38	42.24	0.4072	0.8571
40	42.12	0.3630	0.8559
42	41.88	0.3300	0.8548
44	41.70	0.3000	0.8539
46	41.46	0.2740	0.8524
48	41.26	0.2500	0.8513
50	41.08	0.2270	0.8501
52	40.88	0.2050	0.8489
54	40.72	0.1830	0.8477
56	40.57	0.1660	0.8466
58	40.34	0.1520	0.8454
60	40.27	0.1400	0.8442
62	40.12	0.1290	0.8430
64	39.98	0.1190	0.8418
66	39.84	0.1100	0.8407
68	39.70		0.8395
70	39.57		0.8383

σ = dynes/cm.

μ = cm^2/sec.

ρ = grm./$cm.^3$

The physical properties of water were obtained from the literature, as follows:

Viscosity	(16) p. 374
Density	(16) p. 175
Specific heat	(16) p. 225
Thermal conductivity	(16) p. 459

APPENDIX IV

EXPERIMENTAL DATA

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	7	Outlet Oil °C	Inlet Oil °C	Flow Rate grms./sec
1.6	33.49	33.47	33.08	32.75	32.81	32.93	33.43	44.6	1.685
1.12	33.95	34.18	33.89	33.71	33.55	33.95	33.95	46.15	1.735
1.18	35.0	35.0	34.90	34.5	34.27	34.65	34.75	46.36	1.615
1.24	35.51	35.51	35.11	35.17	34.99	34.95	34.95	47.19	1.660
1.30	36.02	36.02	35.71	35.68	35.78	35.75	35.75	42.79	1.613
1.36	36.52	36.62	36.58	36.18	36.18	35.88	36.45	48.00	1.640
1.42	37.23	37.23	36.92	36.68	36.77	36.75	36.85	48.22	1.679
1.48	37.84	37.84	37.43	37.18	37.17	37.15	37.45	48.22	1.652
1.54	38.04	38.04	37.93	37.67	37.76	37.75	37.95	48.22	1.525
1.60	38.54	38.54	37.44	38.16	37.96	38.15	37.95	48.73	1.488
	2	3	4	5	6	X			
2.6	37.53	37.53	36.92	36.67	36.77	36.50	36.75	54.11	2.228
2.12	38.54	38.54	38.14	37.97	37.76	37.70	37.95	54.30	2.270
2.18									
2.24	40.27	40.27	39.96	39.65	39.80	39.60	39.95	51.68	2.260
2.30	41.07	41.12	40.77	40.45	40.50	40.45	41.0	52.65	2.225
2.36	41.88	42.13	41.50	41.47	41.24	41.10	41.41	52.65	2.185
2.42	42.59	42.95	42.23	41.97	42.10	41.95	42.03	52.64	2.190
2.48	43.27	43.37	43.06	42.69	42.86	42.86	42.86	53.33	2.240

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
2.54	43.90	44.19	43.89	43.49	43.36	43.25	43.68	53.62	2.180
2.60	44.6	44.7	44.3	43.9	44.1	44.00	44.10	54.61	2.270
3.6	36.82	36.52	36.42	35.98	35.77	35.60	35.95	50.22	2.765
3.12	38.03	37.83	37.63	37.37	36.98	36.90	37.50	52.65	2.765
3.18	39.55	39.55	38.94	38.66	38.45	38.25	38.75	53.13	2.945
3.24	40.86	40.39	40.18	39.95	39.78	39.55	40.00	54.10	2.820
3.30	41.58	41.62	41.22	40.96	41.00	40.90	41.57	54.61	2.860
3.36	42.65	42.58	42.55	42.08	42.03	41.93	42.61	54.61	2.760
3.42	43.68	43.29	43.28	42.68	43.06	42.45	43.17	54.61	2.850
3.48	44.4	44.3	44.3	43.9	43.90	43.75	44.40	55.11	2.880
3.54	45.21	45.12	45.12	44.25	44.61	44.50	45.00	55.11	2.580
3.60	45.70	45.64	45.64	45.18	45.14	44.96	45.71	55.12	2.970
4.6	38.24	38.24	37.44	37.17	36.77	36.50	36.75	52.33	6.120
4.12	40.08	40.06	39.48	38.86	38.96	38.70	38.75	55.11	5.775
4.18	41.93	41.88	41.42	40.66	40.48	40.25	40.50	55.92	5.780
4.24	43.67	43.29	43.06	42.68	42.25	42.05	42.30	56.62	5.940
4.30	45.21	44.92	44.62	43.90	43.90	43.70	43.66	57.13	5.930
4.36	46.21	46.15	45.65	45.44	45.13	45.00	45.00	57.64	5.810
4.42	47.02	46.97	46.67	46.31	46.16	46.00	46.21	57.94	5.900
4.48	48.23	48.00	47.70	47.41	47.20	47.00	47.22	58.14	5.940
4.54	48.84	48.83	48.73	47.94	48.21	47.80	48.03	58.14	6.020
4.60	49.75	49.45	49.45	49.00	49.03	48.60	48.75	58.14	5.620

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
5.6	32.78	32.45	32.37	31.97	31.86	31.75	32.43	45.3	1.778
5.12	33.2	33.20	33.09	32.94	32.94	32.90	32.93	46.36	1.785
5.18	34.0	34.0	33.89	33.71	33.78	33.65	33.95	47.39	1.819
5.24	34.8	35.0	34.20	34.5	34.6	34.45	34.75	48.21	1.830
5.30	35.51	35.61	35.71	35.69	35.49	35.45	35.45	53.18	1.895
5.36	36.51	36.51	36.41	36.18	36.18	36.10	36.45	51.20	1.865
5.42	37.23	37.22	37.12	36.88	36.98	36.85	36.95	54.10	1.874
5.48	38.04	38.04	37.93	37.67	37.78	37.55	37.75	55.11	1.880
5.54	39.04	39.04	38.94	38.66	38.45	38.35	38.45	56.12	1.9910
5.60	39.55	39.55	39.76	39.15	39.15	39.10	39.47	56.12	1.878
6.6	31.97	31.93	31.66	31.77	31.33	31.22	31.92	44.2	1.411
6.12	32.58	32.55	32.07	31.97	31.82	31.65	32.42	44.2	1.420
6.18	32.98	32.95	32.67	32.74	32.72	32.65	33.14	44.7	1.485
6.24	33.48	33.55	33.08	32.94	32.92	32.80	33.47	45.0	1.562
6.30	33.99	34.18	33.68	33.72	33.77	33.65	34.20	45.21	1.462
6.36	34.50	34.60	34.40	34.20	34.20	34.15	34.60	45.21	1.502
6.42	35.01	35.01	34.90	34.70	34.80	34.70	35.20	45.21	1.468
6.48	35.41	35.51	35.10	35.19	35.19	35.10	35.50	45.41	1.4610
6.54	35.81	36.01	35.71	35.49	35.59	35.45	35.80	45.41	1.4900
6.60	36.18	36.18	36.01	35.89	35.98	35.80	36.20	45.71	1.5780
7.6	34.50	34.50	34.40	34.20	33.95	33.90	34.45	51.98	2.056
7.12	35.21	35.51	35.10	34.90	34.99	34.90	35.15	52.65	1.978
7.18	36.22	36.22	35.91	35.68	35.99	35.60	36.15	52.94	2.020
7.24	37.02	37.02	36.92	36.67	36.78	36.68	36.95	53.62	2.130
7.30	38.04	38.04	37.73	37.67	37.46	37.42	37.95	54.12	2.335

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
7.36	38.84	39.04	38.44	38.26	38.15	37.95	38.95	53.13	2.135
7.42	39.95	39.95	39.45	39.20	39.15	39.05	39.48	52.93	2.182
7.54	41.30	41.30	40.80	40.67	40.80	40.70	41.04	50.22	2.130
7.60	42.13	41.93	41.82	41.47	41.52	41.46	41.56	50.71	2.245
8.6	35.21	35.21	34.90	34.70	34.80	34.70	34.95	56.92	2.752
8.12	36.98	36.98	36.42	36.18	36.18	36.00	36.15	48.12	2.722
8.18	38.24	38.24	37.93	37.67	37.46	37.35	37.45	49.75	2.825
8.24	39.55	39.55	39.15	38.66	38.75	38.60	38.95	51.40	2.762
8.30	40.9	40.87	40.2	39.85	39.97	39.75	39.97	52.35	2.870
8.36	41.61	41.57	41.01	40.66	40.80	40.60	41.23	53.13	2.800
8.42	42.65	42.58	42.25	41.67	41.83	41.60	41.88	53.90	3.030
8.48	43.7	43.59	43.08	42.69	42.86	42.65	42.90	54.30	2.840
8.54	44.7	44.31	44.11	43.69	43.60	43.50	43.65	55.11	2.915
8.60	45.41	45.13	45.13	44.19	44.30	44.10	44.70	55.62	3.018
9.6	38.03	37.83	37.12	36.88	36.78	36.50	36.45	47.70	3.010
9.12	39.54	39.04	38.74	38.16	37.96	37.85	37.95	49.25	3.155
9.18	40.55	40.05	39.75	39.25	39.15	39.05	39.15	50.03	3.200
9.24	41.59	41.06	40.48	40.46	40.19	39.85	40.00	50.23	3.100
9.30	42.33	42.08	41.82	41.17	41.21	41.05	41.05	50.71	3.162
9.36	43.16	42.89	42.55	42.18	42.05	41.95	42.09	51.20	3.310
9.42	43.98	43.79	43.48	42.89	42.94	42.80	42.98	51.70	3.210
9.48	44.8	44.3	44.1	43.80	43.6	43.45	43.69	51.98	3.065
9.54	45.21	45.13	45.13	44.2	44.3	44.2	44.40	52.16	3.180
9.60	46.02	45.63	48.33	44.75	45.12	44.50	45.00	52.36	3.275

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
10.6	36.82	36.82	36.42	35.88	35.78	35.60	36.15	55.92	4.140
10.12	38.54	38.24	37.93	37.17	37.17	37.00	37.45	51.33	3.700
10.18	39.45	39.25	39.15	38.66	38.56	38.32	38.75	57.94	4.030
10.24	40.58	40.26	40.18	39.85	39.76	39.60	39.95	58.34	4.165
11.6	35.21	35.21	34.9	34.7	34.8	34.6	34.75	55.62	1.935
11.12	36.21	36.21	36.11	35.69	35.78	35.60	35.95	55.92	1.935
11.18	37.53	37.23	36.92	36.68	36.48	36.30	36.75	56.12	2.000
11.24	38.44	38.24	38.13	37.67	37.26	37.55	37.75	55.91	1.995
11.30	39.55	39.25	39.15	38.66	38.76	38.60	38.95	53.62	2.030
11.36	40.45	40.25	39.96	39.65	39.55	39.30	39.75	53.91	2.110
11.42	41.6	41.27	41.0	40.46	40.48	40.20	40.48	54.50	2.110
11.48	42.51	42.07	41.78	41.47	41.21	41.00	41.51	55.11	2.105
11.54	43.30	43.09	42.85	42.18	42.24	42.05	42.23	56.32	2.150
11.60	44.12	43.90	43.88	42.68	43.06	42.78	43.06	57.33	2.170
12.6	40.07	40.06	35.45	38.85	38.76	38.55	39.15	54.30	2.710
12.12	41.90	41.47	41.0	40.66	40.50	40.40	40.81	55.52	2.735
12.18	42.96	42.89	42.23	41.88	41.82	41.75	42.08	56.62	2.762
12.24	44.18	44.10	43.58	43.06	43.06	42.95	43.14	57.33	2.762
12.30	45.3	45.21	44.52	44.3	44.10	43.90	44.7	58.14	2.785
12.36	46.35	46.42	46.15	45.60	45.64	45.50	45.71	58.94	3.260
12.42	47.19	47.23	47.19	46.88	46.87	46.75	46.72	59.35	2.710
12.48	48.53	48.23	47.80	47.72	47.61	47.50	47.63	59.35	2.742
12.54	48.73	48.84	48.43	48.14	48.22	48.05	48.24	59.94	2.675
12.60	49.45	49.45	49.25	48.99	49.04	48.95	48.95	60.14	3.015

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
13.6	41.58	41.26	40.18	39.65	39.75	39.50	39.45	57.13	3.415
13.12	43.95	43.08	42.55	41.67	41.81	41.50	41.57	58.93	3.410
13.18	45.81	45.12	44.30	43.70	43.68	43.50	43.34	60.14	3.4000
13.24	47.23	46.95	45.95	45.59	45.34	45.15	45.21	60.64	3.422
13.30	48.43	48.39	47.39	46.88	47.00	46.55	46.72	61.33	3.455
14.6	42.08	42.08	40.98	40.46	40.00	39.65	40.00	53.90	3.265
14.12	43.89	43.78	42.85	42.08	41.97	41.40	41.88	55.11	3.270
14.18	45.33	45.21	44.90	43.90	43.90	43.40	43.70	56.11	3.280
14.24	46.97	46.43	45.74	45.15	45.12	44.65	45.11	56.62	3.260
14.30	48.41	48.22	47.70	47.05	46.98	46.73	47.03	57.14	3.328
14.36	48.84	48.74	48.24	47.80	47.39	47.15	47.23	57.63	3.230
14.42	50.05	50.05	49.45	49.00	48.74	47.68	48.75	58.14	3.240
14.48	50.74	50.44	50.24	49.84	49.73	49.50	49.44	58.14	3.301
14.54	51.43	51.23	51.03	50.64	50.40	50.30	50.24	58.14	3.285
14.60	52.22	52.02	51.72	51.22	51.21	50.80	51.23	58.14	3.240
15.6	44.78	44.29	43.58	42.68	42.54	42.15	42.09	57.33	3.945
15.12	46.73	46.13	45.33	44.75	44.60	44.10	44.20	58.95	3.900
15.18	48.24	48.20	47.70	46.67	46.38	46.05	46.22	60.14	4.145
15.24	50.04	49.44	49.04	48.44	48.21	47.90	48.03	61.38	4.010
15.30	50.74	50.44	50.24	49.85	49.44	49.20	50.04	61.73	3.870
15.36	52.23	52.56	51.43	51.16	50.53	50.40	50.24	62.91	4.095
16.6	42.33	42.08	41.82	41.17	41.01	40.80	41.03	51.33	2.282
16.12	43.96	43.89	43.06	42.69	42.55	42.35	42.72	58.14	2.290

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
16.18	45.00	44.60	44.30	43.70	43.90	43.60	43.99	58.94	2.290
16.24	46.02	45.73	45.33	44.75	44.92	44.45	45.00	59.35	2.335
16.30	47.02	46.96	46.36	45.80	45.95	45.70	46.01	59.94	2.320
16.36	48.03	47.79	47.39	47.09	46.99	46.80	47.23	60.64	2.422
16.42	49.04	48.62	48.42	47.94	48.00	47.25	48.03	60.64	2.375
16.48	49.85	49.65	49.45	48.80	48.85	48.50	48.74	60.93	2.310
16.54	50.43	50.23	50.03	49.65	49.45	49.25	49.75	60.93	2.382
16.60	51.01	51.01	50.41	50.25	50.20	49.90	50.25	61.13	2.382
17.6	41.57	41.90	40.80	40.26	39.97	39.70	40.00	56.12	2.710
17.12	42.88	42.95	42.04	41.67	41.53	41.40	41.25	56.63	2.960
17.18	44.09	44.20	43.58	42.69	42.86	42.65	42.96	56.93	2.79000
17.24	45.13	45.21	44.93	43.90	43.90	43.70	43.98	57.13	2.720
17.30	46.14	46.21	45.64	44.95	45.12	44.70	45.21	57.13	2.775
17.36	46.79	46.73	46.15	45.80	45.65	45.45	45.71	56.12	2.675
17.42	47.70	47.43	46.99	46.63	46.66	46.30	46.41	56.63	2.810
17.48	48.40	48.44	48.00	47.38	47.20	47.00	47.23	57.63	2.790
17.54	49.23	49.04	48.63	48.16	48.01	47.80	48.24	58.14	2.790
17.60	50.04	50.04	49.44	49.00	49.02	48.80	48.74	58.14	2.780
18.6	50.25	49.85	49.25	48.50	48.00	47.60	48.03	63.13	3.464
18.12	51.73	51.40	51.20	50.54	50.21	49.95	50.05	64.10	3.540
18.18	53.42	53.14	52.34	52.03	51.94	51.65	51.73	65.32	3.485
18.24	55.0	54.35	54.15	53.82	53.20	52.95	53.21	66.14	3.480
18.30	55.98	55.96	55.36	54.00	54.50	54.00	54.70	67.16	3.490

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
19.6	44.90	44.40	42.55	42.28	41.86	41.70	41.60	59.15	3.625
19.12	46.93	46.41	45.33	44.75	44.10	43.70	44.00	60.93	3.655
19.18	49.44	49.24	47.80	46.91	46.99	46.75	47.02	61.62	3.600
19.24	50.74	50.44	50.04	49.00	48.93	48.65	48.95	67.62	3.590
19.30	52.03	52.03	51.43	50.84	50.40	50.20	50.44	63.34	3.605
20.6	42.08	41.93	40.80	40.05	39.96	39.60	39.75	63.11	2.518
20.12	44.10	43.99	42.65	41.88	41.82	41.60	41.56	63.91	2.555
20.18	45.62	45.60	44.92	43.70	43.90	43.65	43.36	64.10	2.499
20.24	47.15	47.02	46.35	45.60	45.12	45.00	45.21	64.10	2.520
20.30	48.69	48.43	47.39	46.98	46.69	46.50	46.72	64.10	2.485
20.36	49.85	49.75	49.04	48.16	48.22	47.95	48.53	64.3	2.450
20.42	50.73	50.42	50.22	49.85	49.41	49.25	49.45	64.3	2.590
20.48	51.73	51.68	51.20	50.25	50.20	50.00	50.23	64.3	2.470
20.54	52.72	52.56	52.16	51.23	51.34	54.15	51.23	64.3	2.510
21.6	44.30	43.68	42.85	41.88	41.51	41.25	41.24		3.290
21.12	46.66	46.21	45.33	44.53	44.10	43.75	44.20	67.9	3.210
21.18	49.04	48.44	47.70	46.88	46.36	46.10	46.22	67.9	3.201
21.24	50.46	50.26	49.86	48.80	48.44	48.25	48.44	67.7	3.148
21.30	52.22	51.73	51.23	50.55	50.21	50.05	50.24	67.6	3.225
21.36	53.41	53.21	52.72	52.22	51.92	51.65	51.73	67.5	3.160
21.42	54.7	54.4	54.2	53.21	53.04	52.95	53.21	67.3	3.165
21.48	55.78	55.38	55.18	54.81	54.21	53.95	54.20	67.3	3.158
21.54	56.68	56.18	56.18	55.81	55.21	54.95	55.21	67.1	3.320
21.60	57.37	57.17	56.97	56.22	56.02	55.90	56.22	67.1	3.200

(continued)

Run No.	Thermometer Readings in Water Bath 2	3	4	5	6	X	Outlet Oil °C	Inlet Oil°C	Flow Rate grms./sec.
22.6	48.73	47.43	46.67	45.60	45.12	44.95	45.21	71.1	3.655
22.12	50.74	50.22	49.25	48.50	48.00	47.80	48.24	71.1	3.738
22.18	53.02	52.35	51.97	51.03	50.20	49.70	50.24	71.1	3.938
22.24	54.99	54.61	53.61	53.01	52.55	52.30	52.71	71.6	3.905
22.30	56.97	56.32	55.72	55.01	54.61	54.40	54.50	72.9	4.150
23.6	45.33	45.21	43.88	42.48	41.82	41.50	41.88	66.1	4.235
23.12	49.75	48.74	47.39	46.24	45.98	45.60	48.41	68.7	4.295
23.18	52.22	51.23	50.22	49.22	49.04	48.75	48.84	70.1	4.255
23.24	54.70	53.80	52.65	52.02	51.65	51.50	51.43	70.6	4.340
23.30	56.37	55.68	55.11	54.00	54.00	53.70	53.80	71.3	4.340
24.6	47.60	47.23	45.05	43.89	43.49	43.25	43.35	74.1	4.575
24.12	51.44	51.03	49.04	48.60	48.00	47.25	47.84	74.88	4.440
24.18	55.19	54.20	52.36	52.02	51.35	51.05	50.24	75.86	4.635
24.24	57.96	57.37	55.31	54.8	54.5	54.35	54.71	76.55	4.760
24.30	60.14	59.75	58.34	57.23	57.23	57.00	57.42	77.24	4.675

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